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By Paul A. Palo

NCEL
Technical Note

Sponsored By Naval Facilities
Engineering Command

CURRENT-INDUCED VESSEL FORCES AND YAW MOMENTS FROM FULL-SCALE MEASUREMENTS.

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NAVAL CIVIL ENGINEERING LABORATORY, PORT HUENEME, CALIFORNIA 93043

METRIC CONVERSION FACTORS

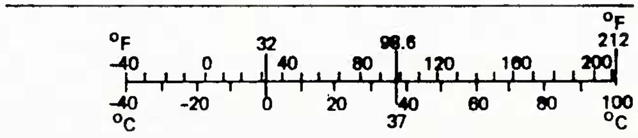
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2,000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1,000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



CONTENTS

Page

INTRODUCTION

Project Objective

The objective of the experiments described here was to collect reliable information on the forces and yaw moment induced on moored ships by an incident current and to use that information to evaluate existing or develop new calculation techniques.

A full-scale test was selected because of the uncertainties inherent in small-scale model testing. The measurements, which are presented in terms of nondimensional coefficients, are used to evaluate existing current loads methodologies.

Background

The Naval Facilities Engineering Command (NAVFAC) is responsible for designing and maintaining fleet and fixed moorings. In support of this, NAVFAC sponsors research and development at the Naval Civil Engineering Laboratory (NCEL), including projects related to anchor technology and computer-based simulation techniques.

In 1979 NCEL found that existing methodologies for estimating the wind- and current-induced steady loads on moored ships were subject to large uncertainties (Ref 1). Investigations into wind- and current-induced vessel loads were initiated. The investigation of wind loads provided a new design methodology based on analysis of wind tunnel data (Ref 2). The investigation into current loads revealed that the available information was unusable for design purposes and that full-scale tests were the only reliable method to resolve the problem (Ref 3). NCEL conducted a full-scale test in 1982 (Ref 4) that resulted in limited measurements of the current-induced loads on a World War II destroyer. Research was also initiated to develop and validate a simulation model for current loads; Reference 5 describes a free-streamline mathematical model to be used as the basis for this new capability.

At about the same time NAVFAC started revising its Design Manual for Harbor Facilities (DM-26) (Ref 6). NCEL proposed a full-scale experiment to measure current loads in support of the NAVFAC design manual revision. This proposal was accepted and funded by the NAVFAC Engineering Investigation Board, and the test program was conducted in the summer of 1983.

The test was conducted using a T-2 tanker (ex-MISSION SANTA YNEZ) from the Maritime Administration (MARAD) Reserve Fleet in Suison Bay, Calif., and the U.S.S. PAUL F. FOSTER (DD-964), a Spruance class destroyer. These vessels were selected because they represented streamlined and nonstreamlined hull forms with comparable hull sizes. The T-2 tanker was filled with seawater and moored by the bow and stern in a river; measurements of the mooring forces were taken for 5 days while the tidal current changed and the seawater was pumped out. (A full test description is provided later in the report.) The Spruance class destroyer was tested primarily in a single-point mooring for 1 day, 1 month later, at the same site.

This report presents the measurements of the current and wind loads on both vessels. These data are used along with the destroyer data in Reference 4 to evaluate existing current loads methodologies, particularly, NAVFAC'S DM-26 and its successor, DM-26.5 (Ref 8).

TEST DESCRIPTION

Test Objective

The test objective was to collect full-scale data to validate NAVFAC'S current loads methodology. The primary test parameters were current speed, gradient, and direction; hull shape; and the water depth-to-draft ratio.

Test Vessels

Selection of the test vessels was a major concern, given that they would have to represent the large variety of hull types used by the Navy. A cargo-type vessel and a surface combatant were selected as representative of the two "extremes" in conventional hull design. In addition, the vessels should be approximately the same size to avoid extrapolation errors when comparing the loads on both hulls. The combatant must have a large sonar bow dome to be typical of modern hulls. Data collected for these vessels would serve two purposes: (1) provide direct measurements on the two most common (by number) Navy hull forms, and (2) provide load estimates on other vessels by interpolation between these two different hull shapes.

A T-2 tanker (ex-MISSION SANTA YNEZ) was approved for use in this test on loan from the Maritime Administration Reserve Fleet in Suison Bay, Calif. Information on the T-2 is provided in Table 1 and Figure 1. Selection of the tanker was also important because the draft could be varied during the test by filling the tanks with seawater and pumping it out. This provided two significant improvements to the test program: (1) it allowed for a more comprehensive parametric study versus hull parameters, and (2) it precluded the need for two test sites to get two different water depth-to-draft ratios. Instead, shallow water and deep water effects could be measured at the same site, provided the water depth was carefully specified.

The surface combatant assigned to these tests was the U.S.S. PAUL F. FOSTER (DD-964), a Spruance class destroyer. Information on this vessel is provided in Table 1 and Figure 2. This vessel satisfied the requirement of having about the same dimensions as the T-2.

Test Site

The test site was in northern San Francisco Bay, Calif., in the Carquinez Straits. This site provided a fairly uniform water depth that resulted in water depth-to-draft ratios of between 2.5 and 6, with the latter value assumed to be equivalent to deep water conditions. This site also provided dependable, large, current speeds, and access to both the MARAD Reserve Fleet and the Naval Supply Center (NSC) Oakland, where all staging was conducted. There were no waves at this site, so the incident current flow field was steady.

Test Procedure

The requirement was to hold the test vessel at a fixed orientation in the current, allow the system to come to equilibrium, record data for 10 minutes, reconfigure the system to provide a different vessel orientation, and repeat the test. The test configuration adopted to accomplish this is shown in Figure 3.

Two moorings were preinstalled as shown in Figure 3. Each test vessel was moored by the bow to the mid-channel buoy throughout the test. For tests requiring a finite incident current angle, a stern hawser was attached to the test vessel from a winch that was mounted on a Navy YC barge moored to the channel-edge buoy. Figure 4 shows a typical configuration during the test (compare to Figure 3).

During the T-2 tests a second YC barge was moored alongside the vessel. vessel. This barge supported a fuel truck and three 3,000-gpm NAVFAC "FIREFLY" water pumps that pumped the seawater out of the tanker while on site; the T-2 was preloaded and arrived at the site at maximum displacement.

INSTRUMENTATION

Data were collected in five separate subsystems during the test, as shown in Figure 5. The primary data collection system was a data collection computer onboard the test vessel (subsystem #1 in Figure 5). The other subsystems included the laser transit subsystem, the YC winch barge subsystem, the Oregon State University (OSU) current sensor subsystem A, and the OSU current sensor subsystem B. These five subsystems are described in the following.

Description of Subsystems

Test Vessel Subsystem. Data were sampled at 0.5-second intervals and stored on floppy disks using a DEC MINC (PDP)-11/03 computer. The following parameters were measured using this subsystem:

Test Parameter	Sensor	Location
Bow/stern hawser tension	Strainsert Model STL-80 tension link	On deck
Bow/stern hawser vertical angle Bow/stern hawser horizontal angle	Humphrey pendulum potentiometer	15 ft outboard of hull on hawser

Test Parameter	Sensor	Location
Vessel heading	Endeco Type 869 solid state compass VDO Model Adis 360 compass	Test van
Wind speed Relative wind direction off bow	Bendix Friez 135	18 ft above mid-ship superstructure

Laser Transit Subsystem. A laser transit was used to measure the vessel heading with respect to shore landmarks, the hawser orientations relative to the vessel keel, and the distance between the transit and a reflector mounted on the YC winch barge. All readings were taken manually. The following test parameters were measured:

Test Parameter	Measurements	Analysis
Vessel heading	Up to six angles using various landmarks	Triangulation provided vessel heading and position
Bow hawser relative angle	Angle to the bow mooring buoy	Used with known hawser length and transit location on vessel to resolve oblique triangle
Stern hawser relative angle	Angle to the YC winch barge and distance from transit to the winch barge	Used with transit location on ship to resolve oblique triangle

YC Winch Barge Subsystem. A Kaye Model DR3-3C Digistrip III data logger was used to record "undisturbed" environmental parameters. The data logger collected analog signals, averaged these signals to get 10-second values, stored those digital averages, and then digitally averaged them over 5 minutes. The following parameters were measured using this subsystem:

Test Parameter	Sensor	Location
Vertical wind gradient	Coastal Navigator Model WSD200 anemometer	Three sensors mounted 21, 31, and 38 ft above the water
Barge heading	VDO Model Adis 360 compass	Mounted 15 ft above the barge deck

Test Parameter	Sensor	Location
Current speed and magnetic direction	Marsh-McBirney Model 555	Suspended 13 ft below the barge draft
Current speed and relative direction	Marsh-McBirney Model 551	Rigidly mounted 9 ft below the barge draft

OSU Subsystem A. This subsystem, suspended from the YC barge and operated by Oregon State University personnel, continuously measured north and east components of current and internally recorded either 1-second (burst mode) or 1-minute analog-averaged (vector-averaging) values. The following parameters were measured:

Test Parameter	Sensor	Location
Current speed and magnetic direction	Neil Brown vector-averaging acoustic current meter	Suspended 13 ft below the barge
Current field characteristics (512 seconds at 1 sample per second, every 2 hr)	Neil Brown burst mode acoustic current meter	Suspended 6 ft below the barge

OSU Subsystem B. This current meter string was moved to various locations throughout the tests to supplement the subsystem B data. One-minute (analog-averaged) readings of current were internally recorded. The following parameters were measured:

Test Parameter	Sensor	Location
Current speed and direction at 10- and 30-ft depths	Neil Brown vector-averaging acoustic current meters	Varied; typically at mid-channel at the upstream crown buoy

Description of Wind and Current Measurements

The wind field was measured at the test vessel and at the YC barge, where a vertical string measured the profile up to 38 feet. Additional wind data were provided from an active system on the DD-964. The YC barge is shown in Figure 6.

The current field was considered vitally important, and six current meters were used. Two NCEL and two OSU current meters (vector-averaging) were independently used at the YC barge at various depths. Two more OSU meters were rigged below a surface buoy at 10- and 30-foot depths. This string was positioned to record the current characteristics at mid-stream by attaching to the mid-stream crown buoys (over the anchors). In this way the current was measured off the bow and stern and at different depths, thus measuring the total flow field around the test vessel. Only limited current measurements were taken at the test vessel.

DATA COLLECTION AND PREPARATION

T-2 Test Schedule

The T-2 tests were conducted on 25-29 August 1983. Six head-on tests at two different drafts were completed. Four tests were conducted at the full 31-foot draft with oblique incident current angles. Twenty-eight tests were conducted at oblique angles at intermediate drafts. Figures 7 and 8 show the T-2 at full and light drafts.

DD-964 Test Schedule

The Spruance class destroyer was tested for 20 hours on 22-23 September 1983. Five tests were conducted for near beam-on currents; another 15 tests were conducted with head-on currents. Figure 9 shows the Spruance class destroyer while on-site.

Data Reduction

Data reduction consisted of two parts. First, the digital data were converted to engineering units using the appropriate calibration factors. Second, redundant and correlated measurements were compared for accuracy and repeatability. For example, the difference between the measured ship magnetic heading and a measured hawser magnetic heading must be equal (i.e., correlated) to a direct measurement of the relative hawser angle with respect to the keel. All the vessel, hawser, and environmental angles were confirmed in this manner. (The ship magnetic heading and relative wind angle on the test vessels were similarly compared to the undisturbed wind magnetic angle measured at the barge.) Wind and current velocities were also compared to determine the accuracy of sensors and the spatial characteristics of each excitation.

A sample set of data is included in Appendix A to illustrate the data quality. The wind and current excitations for all the tests are discussed in Appendix B.

Data Interpretation

After data reduction each test was inspected to insure that the data were complete and the system was in equilibrium; otherwise they were discarded. Some tests were stable only over particular segments (typically beginning or end), and only those portions were retained. Finally, some tests showed two stable responses (typically caused by a discontinuity in current speed) and were split into "A" and "B" subtests. Certain events were correlated, such as a sharp rise in current speed and a corresponding sharp rise in the hawser tensions. By such correlations it was determined that the Straits exhibited large spatial differences when the current speed was low, and most of these low speed tests were not used.

A significant event occurred halfway through the T-2 test that was found later to make many of the tests unusable. One of the smaller mid-channel crown buoys (used for securing the OSU current meter string) sank overnight, presumably after being run over. Without that buoy, the current meter string could not be properly positioned at mid-channel during the ebb cycle (the flood cycle position was unchanged). It was discovered during post-test analysis of the current measurements that the ebb flow was not uniform across the Straits because of the large upstream bend in the Sacramento River. Because of this, the current measurements taken at the channel-edge barge do not accurately represent the current characteristics at the mid-channel during ebb flows. As a result, many ebb flow tests were either discarded (one dozen) or are presented with appropriate error bounds on the coefficients.

Conversely, the flood tide was found to be horizontally uniform. This fact was exploited for the DD-964 tests, since the night testing precluded the small boat operations required to periodically move the current meter string to the mid-channel; thus, all current measurements were taken at the YC barge. The Oregon State University current measurements and analysis are contained in Reference 7.

Presentation of Experimental Data

The final data from the valid T-2 tests are presented in Table 2. The DD-964 data are presented in Table 3. Angles are defined in Figure 10.

DATA ANALYSIS

Resolution of Current-Induced Loads

The wind and current loads on the vessels are defined in terms of a longitudinal force (parallel to the keel), a lateral force (perpendicular to the keel), and a yaw moment. These are illustrated in Figure 10. By decomposing the hawser forces into equivalent longitudinal and lateral forces, a free-body diagram of the test vessel can be constructed as shown in Figure 11. From this,

$$\Sigma F_x = 0; \qquad X_c + X_w + X_m = 0 \tag{1a}$$

$$\Sigma F_y = 0; \qquad Y_c + (Y_w + Y_{\Delta w}) + Y_m = 0 \tag{1b}$$

$$\Sigma N_{Bow} = 0; \quad N_w - \left[Y_{\Delta w}\left(\frac{L}{3}\right) + Y_w\left(\frac{L}{2}\right) + Y_c\, \ell_c + Y_s\, L\right] = 0 \tag{1c}$$

where the variables and subscripts are defined in the LIST OF SYMBOLS. The $Y_{\Delta w}$ term approximates for the added wind force from nonlevel drafts present in many of the T-2 tests. It is assumed to be proportional to the area of a triangle (ship length times the draft difference over 2) that represents the "additional" area over the level draft-projected area of the vessel.

The current-induced components in Equations 1a-c are determined using the measured mooring loads and ESTIMATED wind loads from Reference 2. The current-induced yaw moment is then calculated using:

$$N_c = \left(\ell_c - \frac{L}{2}\right) \cdot Y_c \tag{2}$$

Note that X_c, Y_c, and N_c from Equations 1 and 2 are actual experimental loads, including the effects of horizontal current shear, vertical current shear, and vessel trim.

Some adjustments were made to the estimated T-2 wind loads recommended in Reference 2. The use of lateral wind loads directly from Reference 2 made the current loads oppose the incident current for some tests with very small currents. Accordingly, the lateral wind load was reduced by 25% to make those tests "physically realizable." This reduction was used for all the T-2 lateral wind forces only. All the other component T-2 wind loads and the DD-964 loads were used directly from Reference 2. These adjustments had only a small impact on the current loads in most cases.

This reduction of the scale model lateral wind forces can be rationalized in the following manner. The scale used in wind tunnel tests is determined from the facility wind speed capability, with the criteria that the model-scale flow be post-critical (typical Reynolds Number approximately 10^6). Because the characteristic dimension used for the model-scale Reynolds Number is typically the hull length, freeboard, etc., many of the smaller vessel features (smokestack, masts, etc.) may have laminar flow and drag that are not representative of the same full-scale features. Therefore, these model-scale forces can be too high, requiring an adjustment before scaling to full-scale values. This adjustment would be a function of the vessel characteristics (amount and distribution of features) and the associated details in the model, and would be applicable to all the wind forces and moments. A second argument is presented later that further strengthens this need for a reduction of wind tunnel data.

If these arguments are true, then the design methodologies in Reference 2 are conservative, and a general adjustment of between 0.8 and 1.0 would be recommended for all vessels depending on the amount of rails, pipes, masts, etc.

Presentation of Wind- and Current-Induced Loads

Table 4 lists the final resolution of forces and moments for the T-2 tests. Table 5 lists similar information for the DD-964 tests.

Calculation of Coefficients

The lateral and yaw moment coefficients calculated at each incident angle are defined as:

$$C_y(\theta_c) = \frac{Y_c(\theta_c)}{\frac{1}{2}\rho\, L \cdot T \cdot V_c^2} \qquad (3)$$

$$C_N(\theta_c) = \frac{N_c(\theta_c)}{\frac{1}{2}\rho\, L^2 \cdot T \cdot V_c^2} \qquad (4)$$

These coefficients are used when the angle dependency is under inspection.

For most of the analyses, however, it is necessary to compare equivalent coefficient amplitudes. For the lateral force coefficient comparisons an empirically fit angle function was used to extrapolate coefficients from Equation 3 to maximum coefficients. The yaw moment coefficients were not analyzed in this manner.

An "equivalent" longitudinal force coefficient (K) is used to represent the summation of loads that contribute to the total force. This K value is calculated as:

$$K = \frac{X_c}{V_c^2} \tag{5}$$

No angle corrections are required since the relevant tests were all for head-on currents.

The lateral force coefficients are also plotted versus Reynolds Number (R_N), defined as:

$$R_N = \frac{V \cdot \ell}{\nu} \tag{6}$$

For these applications, the following values were used:

$V = V_c$ (not adjusted to $V_c \cdot \sin\theta$ since the equivalent beam-on coefficient is used)
$\ell = 2 \cdot T$ (assuming the vessel to be analogous to a double-body cylinder)
$\nu = 1.4 \times 10^{-5}$ ft²-sec

The normalized vertical current shear (NVS) is also presented for all the tests and is defined as:

$$NVS = \frac{V(30') - V(10')}{V(10')} \tag{7}$$

where V(xx) is the measured current speed at depth xx and V(10') is analogous to an "average" velocity over the hull. NVS is known to be more exponential with depth rather than linear as shown in Equation 7. Therefore, NVS as used throughout this report is approximate only.

The water depth-to-draft ratio is also used as a parameter in the coefficient analysis. "Deep water" is assumed for all the tests except the 25xx series.

Analysis of Deep Water Lateral Force Coefficients (C_y)

The lateral force coefficients for the T-2 are listed in Table 6.

The angle dependence of the deep water lateral force coefficients for the T-2 is shown in Figure 12. Note the use of different symbols to represent the amount of vertical current shear and the presentation of current speeds within the symbols. This information is essential for interpreting the figure.

Several conclusions can be drawn from Figure 12:

(1) There is a clear dependence of C_y on the amount of shear, based on inspection of the data between 75 and 95 degrees.

(2) The uniform flow coefficients (circles) appear to be relatively constant for high current speeds, based on the data between 65 and 80 degrees.

(3) The uniform flow coefficients (circles) are not constant for the lower current speeds, based on the data at 40 and 45 degrees.

(4) The coefficient is still increasing at 95 degrees, based on the large positive shear data (squares) for a 3.5-ft/sec current speed at 90 and 95 degrees.

(5) There is no apparent pattern for the negative current shear data.

An empirical angle function was fitted to the high-speed, uniform-flow coefficients shown in Figure 12. Conclusion (4) above was used along with similar trends evident in Reference 4 to establish that the maximum lateral force coefficient is near 110 degrees. From this, the following angle function for C_y was determined:

$$C_y(\theta_c) \;\propto\; \sin^{1.5}\phi \qquad (8)$$

where $\phi = (\theta_c \cdot 90/110)$ for $\theta_c < 110$ degrees, and $\phi = [90/70 \cdot (\theta_c - 110)]$ for $\theta_c > 110$ degrees. This function was used in Figure 12.

This angle function was then used to extrapolate all the coefficients to their equivalent maximum coefficients at 110 degrees, $C_{y,max}$. This extrapolation was required to resolve the dependence on the vertical shear and the current speed.

Figure 13 shows the T-2 extrapolated coefficients versus current speed and vertical shear. This figure shows that high current speed coefficients are a function of the vertical shear. The contours superimposed on Figure 13 are representative of different levels of shear. From this figure, it was concluded that the magnitude of the lateral force coefficient is sensitive to the incident current shear. The variation in the magnitude was ±50% for the shears in this test. A simple function representing this dependence is:

$$C_{y,max} \;=\; 1.0 + 1.2 \cdot \mathrm{NVS} \qquad (9)$$

This dependence is considered to be a consequence of the difference in streamlines (and resulting pressures) around the hull.

The coefficients in Figure 12 were also plotted versus Reynolds Number, along with coefficients from Reference 4. The data are shown in Figure 14. The uniform flow coefficients show classic Reynolds Number behavior. The increase in magnitude with the vertical shear is also apparent.

The DD-964 lateral force coefficients are listed in Table 7 and plotted in Figure 15 versus Reynolds Number. Note that the T-2 and the DD-964 lateral force coefficients are equivalent at the same (high positive) shears. It is concluded that the lateral force is independent of hull shape.

Analysis of Shallow Water Lateral Force Coefficients (C_y)

The shallow water lateral force coefficients are listed in Tables 8 and 9, plotted in Figure 16 versus Reynolds Number, and plotted in Figure 17 with the deep draft coefficients. The coefficients are not constant, even at a Reynolds Number of 10^7. This may be related to Froude effects due to the elevation and depression of the surface upstream and in the wake, respectively. The coefficient behavior evident in Figure 17 compared to the deep water coefficients makes it difficult to understand and subsequently extrapolate these results to other vessels and water depths. In addition, the velocity dependence of these shallow coefficients means that use of a single-value correction factor as a function of the water depth-to-draft ratio only is not appropriate for estimating the shallow water lateral force. Effects due to the vertical shear are not definable at this time.

Appendix C presents a discussion of suspected vortex shedding that appears in the hawser force measurements for these tests.

Analysis of Yaw Moment Coefficients (C_N)

The calculated yaw moment coefficients and the test parameters that affect them are listed in Table 10. The yaw coefficients for all vessels and water depths are shown in Figure 18, with important parameters included to aid interpretation.

There are no readily discernible patterns apparent for either the T-2 or the DD-964. This lack of organization is considered more a consequence of the number of parameters rather than large experimental uncertainties; the expected sensitivity of the coefficient to changes in the vessel trim and current shears is illustrated in Figure 19.

Figure 13 shows that the lateral force coefficients do not stabilize for the T-2 until the velocity reaches 3 ft/sec. Since the yaw moment is a function of the sectional lateral forces on the hull, the yaw moment coefficients should show similar behavior. Figure 20 is a plot of the T-2 deep water coefficients with current speeds greater that 3 ft/sec. An attempt was made to standardize the experimental deep water T-2 yaw moment coefficients (in Figure 20) by theoretically removing the effects of vessel trim and the current shear. This investigation is discussed in Appendix D.

Conclusions based on inspection of Figure 20 in terms of the trends shown in Figure 19 are that: (1) the minimum yaw moment coefficient is near 0.1, and (2) the zero crossing is beyond 80 degrees, probably between 90 and 100. Specific conclusions are not possible for the maximum positive coefficient based on these data.

With these conclusions, a reinspection of Figure 18 shows that: (1) the DD-826, DD-964, and T-2 have dissimilar coefficients, showing that the yaw moment is a function of hull shape; (2) the nonsteady T-2 shallow water coefficients are due to the low (less than 3 ft/sec) current speed. (Note in Figure 16 that the lateral force coefficients are likewise not constant at these velocities, even though the high Reynolds Number suggests that both of these shallow water coefficients should be constant.) and (3) the shallow water yaw moment coefficient was not constant even for a fixed incident current angle.

Analysis of the Longitudinal Force Coefficients (C_x)

The T-2 data are considered reliable because the wind force was small compared to the current load and because the current meters were positioned directly upstream of the ship.

The T-2 longitudinal coefficients are listed in Table 11 and plotted in Figure 21. As discussed in the Calculation of Coefficients section, an effective scaling factor (K) is presented that represents the summation of all the current load components. Calculation of these coefficients requires a correction for the longitudinal drag of the YC pump barge as shown in the table. Also, the coefficient is calculated using the interpolated current speed near the bottom of the ship (rather than mid-draft) because that is where most of the hull surface area is concentrated. Note that the coefficient is not constant as predicted using standard resistance theory but increases with increasing velocity.

The DD-964 longitudinal force coefficients are listed in Table 12 and also shown in Figure 21. The scatter in coefficients is higher than the T-2 coefficients because the closest current meters were at the channel-edge YC barge rather than directly ahead of the bow. The flood tide coefficients are more accurate than the ebb tide coefficients because the flood tide showed very low horizontal shear compared to the ebb tide.

Two trends can be seen in the data. First, the coefficient decreases with current speed; this is opposite to the T-2 trend. Second, the coefficient does become relatively constant after 2.5 ft/sec if the more accurate flood velocity coefficients only are used; this is in keeping with standard resistance behavior.

It is therefore concluded that the hull form is important (based on the opposing coefficient slope behavior versus current speed), and that the longitudinal drag for "typical" ocean currents (up to 1-1/2 knots) is not adequately predicted using the constant asymptotic coefficient values.

Note the variation in the longitudinal force for the shallow water tests (as shown in Table 4), which shows the same type of sign reversal as the yaw moments. This information on the longitudinal component of the load may be useful in understanding the lateral load phenomena.

VALIDATION OF CURRENT LOADS METHODOLOGIES

The emphasis in the preceding sections has been on identifying the magnitudes, trends, and uncertainties evident in the experimental coefficients. The data collected in this test provide useful information for analyses related to moorings, maneuvering, small-scale modeling, steady drag, hydrodynamics, and resistance/powering.

The immediate application of these data is in validating existing current loads methodologies, specifically the Navy's Design Manuals for Harbor and Coastal Facilities (DM-26) and its replacement for Fleet

Moorings (DM-26.5). The uncertainties associated with the use of state-of-the-art methodologies are summarized in References 1 and 3. The impact of these new measurements, which are the first known set of full-scale current load measurements, is summarized below for the longitudinal force, lateral force, and yaw moment.

Lateral Force Validation

As was shown in Figure 15, the deep water lateral force coefficient varies depending on the shear, but it is relatively independent of hull shape (assuming bilge keels) for a given shear. Figure 22 shows recommended design coefficients (from Reference 3), presumably for uniform flow since most of the data were collected in model test facilities. The empirical value of 1.0 for uniform flow from these full-scale tests is superimposed. This figure shows the error associated with the use of the model data contained in DM-26.

The latest revision to DM-26 (specifically, DM-26.5, Ref 8) presents an alternative design methodology for lateral current loads. A comparison of calculated to measured forces using this new methodology is shown in Figure 23 for the T-2. For the uniform flow forces this new methodology adequately matches the measured forces for current speeds over 3 ft/sec. It could easily be extended to accommodate the higher coefficients due to an incident vertical shear. Therefore, the deep water lateral force guidelines in DM-26.5 are considered adequate for design use.

These data cannot be used to validate shallow water lateral force guidelines because the T-2 shallow water coefficients are not constant at this fixed water depth-to-draft ratio (see Table 9 and Figures 16 and 17). The data do show, however, that the usual assumption that the shallow water correction factor applicable to both the lateral force and yaw moment is a function of only the water depth-to-draft ratio is incorrect. (Recall that this factor equals the shallow water coefficient divided by the equivalent deep water coefficient.) The measurements show that the shallow water lateral force is more complex than expected, but they are not extensive enough to allow for validation of existing techniques or development of alternatives.

Yaw Moment Validation

The discrepancies among state-of-the-art yaw moment methodologies are illustrated in Figure 24 (adapted from Reference 3). Use of the approximate minimum coefficient of -0.1 for the EC-2 indicates that all existing methodologies may be slightly high. The data available from this test do not allow for a reliable validation but do demonstrate the large number of parameters that significantly affect the yaw moment. A general-purpose yaw moment guideline that incorporates these parameters is unavailable.

Longitudinal Force Validation

The components used to estimate the longitudinal drag on the T-2 and DD-964 are described in Appendix E. The resulting high current speed K values are 530 for the T-2 and 630 for the DD-964, which are reasonably close to the experimental values shown in Figure 21. The design methodology in DM-26.5 yields slightly lower values as shown in Appendix E because it disregards the hull form drag term. This discrepancy will increase as the current speed decreases.

Summary of Validations

(1) These full-scale measurements validate deep water lateral and longitudinal force methodologies, provided the current speed is high enough and the vessels are similar in size and shape to the T-2, DD-964, or DD-826. Use of DM-26.5 guidelines is considered acceptable for these forces.

(2) The results have also shown that conventional shallow water correction factors do not adequately represent the shallow water lateral force behavior. However, results from this test cannot be used to establish alternate guidelines.

(3) Because of their nonsteady and complex nature the deep and shallow water yaw moments cannot be expressed in terms of the test parameters. Generally speaking, use of maximum coefficient amplitudes of 0.1 and a zero crossing at 90 degrees is reasonable for ships in deep water, with level trim, and for uniform current fields.

(4) The data have shown that the use of simplified methodologies for all of these coefficients is only valid at high current speeds (greater then 2 knots). This implies that selection of a coefficient for mooring design will often pose problems since many "operational" currents are between 1 and 2 knots. Choice of a coefficient in these cases must be inferred by inspection of the appropriate figures in this report.

(5) The loads measured in this test correspond to a steady incident current with no wave orbital velocities. In the open ocean in the presence of large, short-crested waves, the instantaneous velocity over the hull will be time-varying and may even include local reversals if the orbital velocities are higher than the steady current speed. The flow characteristics under these circumstances will likely result in forces different from the steady forces measured here.

CONCLUSIONS

Lateral Loads

The lateral current force (Y_c) and coefficient (C_y), discussed previously, are defined as:

$$Y_c(\theta_c) = \frac{1}{2} \rho \; L \; T \; C_y(\theta_c) \; V_c^2 \tag{10}$$

$$C_y(\theta_c) = C_{y,max} \cdot f[\theta_c] \tag{11}$$

Conclusions for DEEP WATER lateral force are:

1. C_y is insensitive to the hull shape.

2. $C_{y,max}$ occurs near an incident current direction of 110 degrees.

3. $C_y(\theta_c)$ is proportional to $\sin^{1.5}$.

4. $C_{y,max}$ is 1.0 for uniform flow, but varies between 1.5 for positive shear (current increases with depth), and 0.5 for negative shear.

5. $C_{y,max}$ is constant for Reynolds Numbers above 10^6.

Conclusions for shallow water lateral force are:

1. This coefficient varied almost linearly with velocity for Reynolds Numbers near 10^7 (where the deep water C_y is constant). This behavior is not understood at the present time. The limited data does not allow for the formulation of general correction factors for extrapolation to other vessels or water depths.

2. A single-value "shallow water correction factor" (ratio of shallow water to deep water forces) is therefore undefined based on item 1.

<u>Yaw Moments</u>

The current-induced yaw moment (N_c) and coefficient (C_N) were discussed previously and are defined similarly to the lateral loads:

$$N_c(\theta_c) = \frac{1}{2}\rho \cdot L^2 \cdot T \cdot C_N(\theta_c) \cdot V_c^2 \tag{12}$$

$$C_N(\theta_c) = \left\{ \begin{array}{c} C_{N,min} \\ \\ C_{N,max} \end{array} \right\} f[\theta_c] \quad \text{for} \left\{ \begin{array}{l} 0 < \theta_c < \theta_{zero} \\ \\ \theta_{zero} < \theta_c < 180 \end{array} \right. \tag{13}$$

1. The deep water yaw coefficients exhibit a scatter for each vessel, and the coefficient groups for each vessel are also dissimilar. No trends are apparent versus incident angle, velocity, or vertical shear. This scatter is attributed to the multitude of test parameters that significantly alter the yaw moment as was shown in Figure 19.

2. The magnitude of the shallow water yaw coefficients from the T-2 test show a clear trend versus current speed at a fixed incident angle and fixed water depth-to-draft ratio (shown in Figure 18), which includes a SIGN REVERSAL. Existing methodologies propose a constant

correction factor (which is solely a function of the water depth-to-draft ratio) for these conditions. Therefore, it is concluded that existing techniques are invalid. The limited data from this test are not extensive enough to be used to develop an alternative methodology.

Longitudinal Forces

The current-induced longitudinal force (X_c) is made up of friction drag on the bare hull; added friction drag due to fouling; and form drag on the hull, propellers, and other appendages. While all these component loads have different coefficients and use different projected or surface areas, they are all proportional to the current velocity squared. Since the hull friction coefficient changes only by 5% over the range of test current velocities and all the other coefficients are presumed constant, the longitudinal force can be simplified for head-on flow as:

$$X_c = K \cdot V_c^2 \qquad (14)$$

where $K = \Sigma[(1/2)\rho\ C_D\ A]$ over all the component loads.

Conclusions regarding the T-2 longitudinal force are:

1. K is NOT constant; it increases steadily from 550 to 800 for current speeds between 2.75 and 3.75 ft/sec (Reynolds Number about 10^8 based on length). This increase is contrary to the usual small decrease in C_x versus increased velocity; see item 2 below.

2. The T-2 experimental values are slightly higher than the calculated K value of 530 using established methodologies (including a hull form drag coefficient of 0.06).

Conclusions regarding the DD-964 longitudinal force are:

1. K varies over a wider range from 2,500 to 540 for current speeds between 0.9 and 4.9 ft/sec compared to the T-2 data.

2. More importantly, the decreasing trend of K versus current velocity is opposite the T-2 data. While this trend is closer to "accepted" behavior and appears almost constant for the higher velocities, the amount of change at the lower velocities is much larger than expected.

3. The effective K value calculated using standard techniques is 630 (using a hull form drag of 0.03).

Further information on the theoretically-determined force is included in Appendix E.

Wind

This test has provided useful information for validating the wind load methodologies presented in Reference 2 and 8 which were based entirely on wind tunnel test data. In the data analysis it was found that the calculated lateral wind force was too large, and a 25% reduction was subsequently used for the T-2 tanker tests. The rationale for this reduction was presented in the Resolution of Current-Induced Loads section.

An additional rationale is the strong sensitivity of the lateral current force to the vertical shear (e.g., Figure 13). Wind-induced forces may exhibit the same shear sensitivity. The wind loads methodology in Reference 2 was based on an evaluation of only those tests that included a vertical wind shear (positive shear as defined in this report). However, the wind measurements in this test showed a very uniform flow field above 15 feet. Thus, the positive shear coefficients in Reference 2 would be too high for the uniform flow in this test, and a reduction would be required analogous to Figure 13.

Until additional wind loads data becomes available, all the methodologies presented in References 2 and 8 are considered conservative. Reductions of up to 20% (nominally 10%) may provide more realistic estimates of the true magnitudes of the wind-induced loads.

RECOMMENDATIONS

This report has provided answers to some fundamental current loads questions (e.g., deep water lateral loads) and has shown the inadequacy of some commonly-used design practices (e.g., shallow water correction factors).

While these data do not allow for complete resolution of the vessel-current problem, they can be used as guidelines for further research. Most importantly, the data can be used to validate similitude relationships, which will allow for the confident use of model tests. Also, the load sensitivities presented there will allow subsequent researchers (at any scale) to recognize and properly quantify the effects of the numerous parameters identified here.

Specific recommendations are to conduct model tests to establish their value as a research tool and to continue full-scale testing with particular emphasis on the shallow water phenomena.

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LIST OF SYMBOLS

A	Cross-sectional or surface area
C_D	Drag coefficient
C_N	Yaw moment coefficient
$C_{N,max}$	Positive amplitude of C_N
$C_{N,min}$	Negative amplitude of C_N
C_x	Longitudinal force coefficient
C_y	Lateral force coefficient
$C_{y,max}$	Maximum amplitude of C_y
F_x	Longitudinal force
F_y	Lateral force
K	Effective longitudinal force multiplier
k	Partial longitudinal force multiplier
k_a	Appendage drag longitudinal force multiplier
k_b	Sonar dome drag longitudinal force multiplier
k_f	Friction drag longitudinal force multiplier
k_F	Hull form drag longitudinal force multiplier
k_p	Propeller drag longitudinal force multiplier
L	Ship length (waterline)
ℓ	Characteristic length for Reynolds Number
ℓ_c	Moment arm for lateral current force, from bow
N	Yaw moment about vessel midships
N_{Bow}	Yaw moment about the vessel bow
N_c	Current-induced yaw moment
N_w	Wind-induced yaw moment

R_N	Reynolds Number
T	Ship draft
V	Wind or current velocity
V_c	Current velocity
X	Longitudinal force (parallel to keel)
X_a	Appendage drag (rudder, struts, etc.)
X_b	Form drag on sonar dome and longitudinal component of bow hawser tension in horizontal plane
X_c	Current-induced longitudinal force
X_f	Friction force on hull
X_F	Form drag on hull
X_m	Net longitudinal mooring force
X_p	Propeller drag
X_r	Residual force
X_s	Longitudinal component of stern hawser tension in horizontal plane
X_T	Total longitudinal force
X_w	Wind-induced longitudinal force
Y	Lateral force (perpendicular to keel)
Y_b	Lateral component of bow hawser tension in horizontal plane
Y_c	Current-induced lateral force
Y_m	Net lateral mooring force
Y_s	Lateral component of stern hawser tension in horizontal plane
Y_w	Wind-induced lateral force
$Y_{\Delta w}$	Additional wind-induced lateral force due to vessel trim
θ_b	Hawser angle at bow in horizontal plane
θ_c	Incident current angle
θ_s	Hawser angle at stern in horizontal plane

θ_{zero}	Angle where yaw moment value is zero
ν	Kinematic viscosity of water
ρ	Density of water
ϕ	Angle function based on θ

Table 1. Test Vessel Dimensions

Characteristic	T-2 World War II Tanker	DD-964 Spruance Class Destroyer	DD-826 World War II Destroyer
Length (waterline), ft	503	529	390
Beam, ft	68	55	41
Draft	15-31	19.5[a]	10
Displacement, ℓton	8,000-22,000	8,000	2,400
No. of propellers	1	2	0[b]
Propeller diameter, ft	19.5	17.0	0
Bilge keels	yes	yes	yes
End-projected wind area, ft^2	3,200-4,040	3,700	1,400
Side-projected wind area of hull, ft^2	6,240-12,430	12,200	5,650
Side-projected wind area of superstructure, ft^2	5,000	9,500	4,200
Hull surface area, ft^2	43,200[c]	36,340	16,600
Level of fouling	moderate; some grass along the waterline	low; first deployment after drydock	extreme; several years' growth

[a]Draft of sonar dome was 29.5 ft.

[b]Original two propellers were absent.

[c]At the draft present for the head-on tests.

Table 2a. T-2 Test Conditions

Test No.	Start[a]	Stop[a]	Draft (ft)		Water Depth (ft)		Wind		Current Speed (ft/sec) at location/depth of --			Current Relative Direction[b] (deg)
			Bow	Stern	Bow	Stern	Speed (ft/sec)	Relative Direction[b] (deg)	Mid-Channel		YC Barge 12 ft	
									10 ft	30 ft		
2501	1602	1616	31.0	31.0	78	86	33.6	-65	2.65	3.15	2.95	-60
2502	1631	1648	31.0	31.0	78	86	31.0	-65	2.35	2.85	2.50	-55
2503A	1704	1709	31.0	31.0	78	86	34.5	-70	1.55	1.88	1.70	-55
2503B	1709	1714	31.0	31.0	78	86	34.5	-70	1.60	1.75	1.40	-55
2504	1743	1758	31.0	31.0	78	86	35.4	-65	0.40	1.40	0.50	-60
2602A	1010	1020	19.0	23.0	62	62	13.5	190	3.20	4.25	--	0
2602B	1020	1029	19.0	23.0	62	62	14.5	190	3.20	4.1	--	0
2603A	1037	1047	19.0	23.0	62	62	15.0	190	2.90	3.9	--	0
2603B	1047	1057	19.0	23.0	62	62	15.0	190	2.70	3.8	--	0
2604A	1112	1120	19.0	23.0	62	62	14.0	190	2.45	3.45	--	0
2604B	1120	1128	19.0	23.0	62	62	13.0	190	2.15	3.25	--	0
2605	1305	1317	19.0	23.0	76	84	20.0	-70	1.10	0.20	1.20	-60
2607	1352	1406	19.0	23.0	77	85	23.0	-75	2.60	1.30	1.70	-80
2608	1413	1426	19.0	23.0	78	86	23.0	-75	3.50	3.10	3.10	-70
2609	1436	1456	18.3	23.0	77	84	22.0	-75	4.00	3.25	3.25	-75
2610	1507	1522	17.4	23.0	77	84	24.0	-75	3.50	3.40	3.40	-75
2611	1537	1548	16.3	23.0	76	82	22.6	-80	3.65	3.45	3.50	-80
2612	1602	1615	15.5	23.0	79	87	17.8	-60	3.50	3.40	3.30	-65
2613	1639	1654	15.2	23.0	73	81	20.0	-55	3.10	2.85	3.0	-45
2614	1704	1719	15.1	23.1	72	80	21.1	-40	2.60	2.45	2.50	-40
2615	1735	1745	15.0	23.2	72	80	25.6	-25	1.95	1.80	1.80	-45
2701	0746	0802	13.0	22.0	72	72	20.0	-95	3.50	4.55	4.80	90
2702A	0815	0821	13.0	22.0	71	71	21.1	-85	2.90	4.45	4.50	90
2702B	0822	0830	13.0	22.0	71	71	21.1	-80	3.80	4.30	4.80	90
2703	0840	0855	13.0	22.0	71	71	21.6	-80	3.50	5.15	5.20	95
2704A	0902	0910	13.0	22.0	71	71	22.5	-85	3.30	4.90	5.20	95
2704B	0911	0919	13.0	22.0	71	71	21.1	-80	3.40	5.00	5.20	95
2706	0946	1001	13.0	22.0	64	69	23.2	-90	3.35	4.75	5.10	85
2707	1017	1032	13.0	22.0	62	68	23.0	-115	3.00	3.85	5.00	60

[a] 24-hr time.
[b] Measured counterclockwise from bow (see Figure 10).

Table 2b. T-2 Test Responses

Test No.	Bow Hawser			Stern Hawser		
	Tension (10^3 lb)	Vertical Angle (deg)	Relative Horizontal Angle[a] (deg)	Tension (10^3 lb)	Vertical Angle (deg)	Relative Horizontal Angle[a] (deg)
2501	115.0	2.9	-65	108.0	0	-55
2502	70.0	3.1	-55	65.0	0	-68
2503A	33.0	3.7	-35	35.0	0	-76
2503B	25.0	3.7	-35	25.0	0	-76
2504	12.0	9.3	-25	10.0	0.1	-71
2602A	10.7	7.0	0	--	--	--
2602B	9.9	7.0	0	--	--	--
2603A	7.9	8.5	0	--	--	--
2603B	6.9	8.5	0	--	--	--
2604A	4.6	11.0	0	--	--	--
2604B	3.7	12.0	0	--	--	--
2605	8.9	6.6	-40	8.9	6.5	-49
2607	13.8	6.1	-50	18.0	5.7	-48
2608	57.5	5.0	-60	55.8	5.3	-48
2609	61.0	5.0	-60	57.8	5.3	-48
2610	59.3	5.0	-58	59.2	5.3	-48
2611	77.9	5.0	-58	78.4	5.2	-48
2612	52.5	5.3	-68	49.0	2.4	-54
2613	23.2	6.2	-63	19.8	3.5	-69
2614	17.0	6.8	-72	13.9	5.5	-74
2615	16.8	6.8	-72	16.5	4.5	-75
2701	59.0	5.7	52	82.0	4.4	70
2702A	58.0	5.8	52	75.0	4.5	70
2702B	60.0	5.8	52	87.0	4.5	70
2703	65.8	5.7	52	95.0	4.4	70
2704A	67.0	5.8	52	92.0	4.5	70
2704B	70.0	5.8	52	104.0	4.5	70
2706	67.1	5.6	60	76.0	2.2	69
2707	51.0	6.0	75	39.0	2.6	82

[a]See Figure 10.

Table 3a. DD-964 Test Conditions

Test No.	Wind		Current	
	Speed (ft/sec)	Relative Direction[a] (deg)	Speed (ft/sec)	Relative Direction[a] (deg)
265-03A	14	-35	1.95	-75
-03B	14	-35	1.6	-70
-04	14.5	-55	0.8	-100
-08	24	125	2.6	0
-09A	22	115	1.8	0
-09B	22	115	1.3	0
-10	15	-60	0.9	0
266-01	15	-60	2.7	0
-02	13	-60	3.0	0
-03	12	-60	2.9	0
-05	14	-60	2.8	0
-06	15	-60	2.6	0
-07	12	120	4.9	0
-08	13	95	4.6	0

[a]See Figure 10.

Table 3b. DD-964 Test Responses

Test No.	Bow Hawser			Stern Hawser		
	Tension (10^3 lb)	Vertical Angle (deg)	Relative Horizontal Angle[a] (deg)	Tension (10^3 lb)	Vertical Angle (deg)	Relative Horizontal Angle[a] (deg)
265-03A	46.0	9.2	-36	28.5	1.5	-42
-03B	41.5	9.5	-34	27.0	1.6	-42
-04	16.0	10.0	-68	12.5	1.7	-40
-08	4.0	17.0	0			
-09A	3.35	18.0	0			
-09B	3.20	23.0	0			
-10	3.35	12.0	0			
266-01	8.8	12.0	0			
-02	9.5	12.0	0			
-03	8.5	12.0	0			
-05	9.0	11.0	0			
-06	7.5	14.0	0			
-07	13.0	9.0	0			
-08	12.5	9.0	0			

[a]See Figure 10.

Table 4. T-2 Load Components

Test No.	Mooring[a]			Wind[a]				Current[a]		
	Longitudinal (10^3 lb)	Lateral (10^3 lb)	Yaw Moment (10^6 ft-lb)	Longitudinal (10^3 lb)	Lateral[b] (10^3 lb)	Lateral[b] (Trim) (10^3 lb)	Yaw Moment (10^6 ft-lb)	Longitudinal (10^3 lb)	Lateral (10^3 lb)	Yaw Moment (10^6 ft-lb)
2501	13.4	192.6	-4.06	2.0	-5.8	-1.7	0.44	-15.4	-185.0	3.62
2502	-15.8	117.5	0.67	1.7	-5.0	-1.5	0.36	14.1	-111.0	-1.03
2503A	-18.7	54.8	4.21	1.9	-6.3	-1.8	0.38	16.8	-46.7	-4.59
2503B	-14.4	38.5	2.40	1.9	-6.3	-1.8	0.38	12.5	-30.4	-2.78
2504	-7.6	14.4	1.00	2.1	-6.6	-1.9	0.45	5.5	-6.0	-1.45
2602A	-10.7	0	0	-0.6	0	0	0	11.0	0	0
2602B	-9.8	0	0	-0.7	0	0	0	10.3	0	0
2603A	-7.8	0	0	-0.7	0	0	0	8.4	0	0
2603B	-6.9	0	0	-0.7	0	0	0	7.4	0	0
2604A	-4.5	0	0	-0.6	0	0	0	5.1	0	0
2604B	-3.6	0	0	-0.6	0	0	0	4.1	0	0
2605	-1.0	13.2	0.05	0.7	-3.8	-0.6	0.15	0.3	-8.8	-0.20
2607	0.2	27.4	-0.17	0.8	-5.1	-0.8	0.16	-1.0	-21.5	0.01
2608	8.6	90.9	-2.09	0.7	-5.1	-0.8	0.15	-9.3	-84.9	1.94
2609	8.2	95.4	-2.46	0.7	-4.7	-0.7	0.13	-8.9	-89.9	2.33
2610	8.3	93.9	-1.55	0.9	-5.5	-1.2	0.18	-9.2	-87.1	1.37
2611	11.2	123.8	-1.89	0.7	-4.9	-1.3	0.13	-11.9	-117.6	1.76
2612	9.1	84.9	-1.41	0.7	-2.9	-0.8	0.17	-9.8	-81.1	1.24
2613	-3.5	39.1	-0.49	1.1	-3.4	-1.0	0.24	2.4	-34.6	0.25
2614	-1.4	29.3	-0.69	1.4	-3.2	-0.9	0.27	0	-25.4	0.42
2615	-0.9	32.1	0.06	2.4	-2.5	-0.8	0.34	-1.5	-28.7	-0.40
2701	-8.2	-123.1	2.58	0.1	-4.0	-1.3	-0.05	8.1	128.4	-2.53
2702A	-10.1	-115.7	-3.26	0.4	-4.6	-1.4	0.05	9.7	121.7	3.21
2702B	-7.2	-128.5	-7.80	0.6	-4.6	-1.4	0.12	6.6	134.5	7.68
2703	-8.0	-140.6	-6.23	0.6	-4.8	-1.5	0.10	7.4	146.9	6.13
2704A	-9.8	-138.6	-8.60	0.5	-5.2	-1.6	0.07	9.3	145.5	8.53
2704B	-7.5	-152.3	-9.36	0.5	-4.6	-1.4	0.08	7.0	158.3	9.23
2706	-6.3	-128.7	-8.32	0.3	-5.8	-1.7	-0.03	6.0	135.9	8.35
2707	-7.8	-87.6	-10.30	-0.5	-5.2	-1.7	-0.31	8.3	94.5	10.61

[a]See Figure 10.

[b]Includes reduction from Reference 2 recommendations. The total lateral wind force is the sum of these two columns.

Table 5. DD-964 Load Components

Test No.	Mooring[a]			Wind[a]			Current[a]		
	Longitudinal (10^3 lb)	Lateral (10^3 lb)	Yaw Moment (10^6 ft-lb)	Longitudinal (10^3 lb)	Lateral (10^3 lb)	Yaw Moment (10^6 ft-lb)	Longitudinal (10^3 lb)	Lateral (10^3 lb)	Yaw Moment (10^6 ft-lb)
265-03A	-15.60	45.7	-3.1	1.84	-6.7	0.76	13.76	-39.1	2.34
-03B	-13.90	40.9	-2.2	1.84	-6.7	0.76	12.06	-34.3	1.46
-04	-3.70	22.6	-2.3	1.60	-11.0	0.97	2.10	-11.6	1.32
-08	3.82			-0.81			4.63		
-09A	3.35			-0.68			3.88		
-09B	2.90			-0.68			3.60		
-10	2.80			0.81			2.00		
266-01	8.60			0.81			7.79		
-02	9.10			0.66			8.44		
-03	8.30			0.52			7.80		
-05	6.20			0.70			5.50		
-06	5.60			0.81			4.79		
-07	12.85			-0.20			13.05		
-08	12.35			-0.20			12.55		

[a] See Figure 10.

Table 6. T-2 Deep Water Lateral Force Coefficients

Test No.	Current				Reynolds Number[d] (10^6)	Lateral Coefficients	
	Mean Speed[a] (ft/sec)	Vertical Gradient[b] (ft/sec)	Normalized Gradient[c]	Incident Direction (deg)		$C_y(\theta)$[e]	$C_{y,max}$[f]
2614	2.60	-0.15	-0.06	-40	7.1	0.38	0.96
2613	3.10	-0.25	-0.08	-45	8.4	0.37	0.80
2615	1.95	-0.15	-0.08	-45	5.3	0.78	1.68
2612	3.48	-0.10	-0.03	-65	9.5	0.68	0.95
2608	3.43	-0.40	-0.12	-70	10.3	0.67	0.87
2609	3.88	-0.75	-0.19	-75	11.0	0.57	0.69
2610	3.49	-0.10	-0.03	-75	10.1	0.70	0.85
2611	3.63	-0.20	-0.06	-80	10.2	0.89	1.03
2605	1.00	-0.90	-0.90	-60	3.0	0.81	1.23
2607	2.44	-1.30	-0.53	-80	7.3	0.34	0.39
2707	3.17	0.85	0.27	60	7.9	1.06	1.61
2706	3.45	1.40	0.40	85	8.6	1.28	1.41
2702B	3.92	0.50	0.13	90	9.8	0.98	1.04
2701	3.61	1.05	0.29	90	9.0	1.10	1.17
2702A	3.01	1.55	0.52	90	7.5	1.50	1.60
2703	3.62	1.65	0.46	95	9.1	1.26	1.30
2704B	3.54	1.60	0.45	95	8.9	1.42	1.47
2704A	3.46	1.60	0.46	95	8.7	1.36	1.41

[a]Mean Speed: at mid-ships, at mid-draft.

[b]Vertical Gradient: Velocity (30-ft depth) - Velocity (10-ft depth).

[c]Normalized Gradient: Vertical Gradient/Mean Speed.

[d]Reynolds Number: [Mean Speed x 2 (draft)]/(1.4 x 10^{-5} ft²/sec).

[e]$C_y(\theta)$: Lateral coefficient at that incident angle.

[f]$C_{y,max}$: Coefficient extrapolated to an equivalent beam-on current.

Table 7. DD-964 Deep Water Lateral Force Coefficients

Test No.	Current				Reynolds Number[d] (10^6)	Lateral Coefficients	
	Mean Speed[a] (ft/sec)	Vertical Gradient[b] (ft/sec)	Normalized Gradient[c]	Incident Direction (deg)		$C_y(\theta)$[e]	$C_{y,max}$[f]
265-03A	1.95	0.90	0.46	-75	5.4	1.04	1.18
-03B	1.60	0.90	0.56	-70	4.3	1.43	1.70
-04	0.80	2.1	2.60	-100	2.2	1.72	1.72

[a]Mean Speed: at mid-ships, at mid-draft.

[b]Vertical Gradient: Velocity (30-ft depth) - Velocity (10-ft depth).

[c]Normalized Gradient: Vertical Gradient/Mean Speed.

[d]Reynolds Number: [(Mean Speed x 2 (draft)]/(1.4 x 10^{-5} ft²/sec).

[e]$C_y(\theta)$: Lateral coefficient at that incident angle.

[f]$C_{y,max}$: Coefficient extrapolated to an equivalent beam-on current.

Table 8. T-2 Shallow Water Lateral Force Coefficients for Water Depth/Draft = 2.6

Test No.	Current				Reynolds Number[d] (10^6)	Lateral Coefficients	
	Mean Speed[a] (ft/sec)	Vertical Gradient[b] (ft/sec)	Normalized Gradient[c]	Incident Direction (deg)		$C_y(\theta)$[e]	$C_{y,max}$[f]
2501	2.82	0.50	0.18	-60	12.5	1.47	2.23
2502	2.50	0.50	0.20	-55	11.0	1.13	1.90
2503A	1.66	0.33	0.20	-55	7.4	1.07	1.80
2503B	1.60	0.15	0.09	-55	7.1	0.75	1.26
2504	0.65	1.00	1.53	-60	2.9	0.91	1.39

[a]Mean Speed: at mid-ships, at mid-draft.

[b]Vertical Gradient: Velocity (30-ft depth) - Velocity (10-ft depth).

[c]Normalized Gradient: Vertical Gradient/Mean Speed.

[d]Reynolds Number: [(Mean Speed x 2 (draft)]/(1.4 x 10^{-5} ft²/sec).

[e]$C_y(\theta)$: Lateral coefficient at that incident angle.

[f]$C_{y,max}$: Coefficient extrapolated to an equivalent beam-on current.

Table 9. Shallow Water Correction Factors

Test No.	Mean Current Velocity (ft/sec)	Reynolds Number (10^6)	Normalized Vertical Gradient	Lateral Force		Yaw Moment	
				$C_{y,max}$	Force Correction Factor[a]	C_N	Moment Correction Factor[b]
2501	2.82	12.5	0.18	2.23	1.86	0.058	-0.6
2502	2.50	11.0	0.20	1.90	1.53	-0.021	0.2
2503A	1.66	7.4	0.20	1.80	1.45	-0.213	2.1
2503B	1.60	7.1	0.10	1.26	1.13	-0.139	1.4

[a]Factor = $C_{y,max}$ divided by $C_{y,max}$ in deep water with same gradient (see equ 9).

[b]Factor = C_N divided by -0.1, which is the estimated deep water value at that incident angle under equivalent trim and shear conditions.

Table 10a. T-2 Yaw Moment Coefficients

Test No.	Current					Water Depth	Yaw Moment Coefficient
	Mean Speed[a] (ft/sec)	Normalized Gradients		Normalized Trim[d]	Incident Direction (deg)	Draft (Mean)	
		Vertical[b]	Horizontal[c]				
2501	2.82	0.18	0.03	0	-60	2.6	0.058
2502	2.50	0.20	0.02	0	-55	2.6	-0.021
2503A	1.66	0.20	0.04	0	-55	2.6	-0.213
2503B	1.60	0.09	0.06	0	-55	2.6	-0.139
2504	0.65	1.53	-0.07	0	-60	2.6	-0.447
2614	2.60	-0.06	-0.01	0.42	-40	4.8	0.012
2613	3.10	-0.08	-0.01	0.42	-45	4.9	0.005
2615	1.95	-0.08	-0.03	0.42	-45	4.8	-0.023
2612	3.48	-0.03	-0.03	0.42	-65	5.1	0.021
2608	3.43	-0.12	-0.05	0.19	-70	4.1	0.031
2609	3.88	-0.19	-0.09	0.23	-75	4.2	0.029
2610	3.49	-0.03	-0.01	0.28	-75	4.4	0.022
2611	3.63	-0.06	-0.02	0.34	-80	4.6	0.027
2605	1.00	-0.90	0.05	0.19	-60	4.0	-0.037
2607	2.44	-0.53	0.17	0.19	-80	4.0	0
2707	3.17	0.27	0.30	0.51	60	4.8	-0.056
2706	3.45	0.40	0.23	0.51	85	4.9	0.061
2702B	3.92	0.13	0.12	0.51	90	5.5	0.133
2701	3.61	0.29	0.17	0.51	90	5.5	0.152
2702A	3.01	0.52	0.25	0.51	90	5.5	0.125
2703	3.62	0.46	0.22	0.51	95	5.5	0.159
2704B	3.54	0.45	0.24	0.51	95	5.5	0.157
2704A	3.46	0.46	0.26	0.51	95	5.5	0.191

[a]Mean Speed: current speed at mid-ships, at mid-draft.

[b]Normalized Vertical Gradient: [Velocity (30 ft) - Velocity (10 ft)]/Mean Speed.

[c]Normalized Horizontal Gradient: [Velocity (stern) - Velocity (bow)]/Mean Speed.

[d]Normalized Trim: [Draft (stern) - Draft (bow)]/Mean Draft.

Table 10b. DD-964 Yaw Moment Coefficients[a]

Test No.	Current		Yaw Moment Coefficient
	Mean Speed (ft/sec)	Incident Direction (deg)	
265-03A	1.95	-75	-0.11
-03B	1.60	-70	-0.10
-04	1.15	-100	-0.18

[a]Neither the horizontal nor vertical gradients were measured.

Table 10c. DD-826 Yaw Moment (and Lateral) Coefficients[a] (from Ref 4)

Test No.	Current		Yaw Moment Coefficient	Lateral Coefficient		Reynolds Number[b] (10^6)
	Mean Speed (ft/sec)	Incident Direction (deg)		$C_y(\theta)$	$C_{y,max}$	
1A	0.39	145	0.25	1.16	1.64	0.31
1B	0.37	140	0.20	0.88	1.41	0.34
7	0.69	110	-0.04	1.06	1.06	0.92
8	0.59	60	0.05	0.90	1.19	0.73
9	0.54	95	0.07	0.84	0.88	0.77

[a]Both the horizontal and vertical gradients were essentially zero.
[b]Based on twice the draft as the characteristic dimension.

Table 11. T-2 Longitudinal Forces and Coefficients

Test No.	Environmental Excitations (ft/sec)				Horizontal Mooring Force[b] (klb)	Wind Force[c] (klb)	Pump Barge Current Force[d] (klb)	T-2 Current Force (klb)	K[e]
	Current at Depth of--			Wind					
	10 ft	30 ft	20 ft[a]						
2602A	3.2	4.25	3.75	13.3	-10.66	-0.58	0.24	11.0	803
B	3.2	4.1	3.6	14.5	-9.82	-0.69	0.24	10.3	792
2603A	2.9	3.9	3.4	15.0	-7.81	-0.74	0.17	8.4	725
B	2.7	3.8	3.3	15.0	-6.85	-0.74	0.16	7.4	682
2604A	2.45	3.45	3.0	14.0	-4.55	-0.64	0.12	5.1	563
B	2.15	3.25	2.75	13.0	-3.59	-0.55	0.09	4.1	555

[a] Estimate based on the two previous measured velocities. This speed was used in the analysis because it represents the velocity where most of the hull surface area (and associated friction drag) was concentrated.

[b] Positive forces defined in Figure 10.

[c] Estimated using techniques summarized in Reference 2 for a stern-on wind.

[d] Approximate barge drag, assuming low surface current speed over 3 ft draft and large sheltering due to tanker boundary layer and shadowing. Barge dimensions: 110- by 40- by 3-ft draft by 9-ft freeboard.

[e] See Equation 5. Estimated accuracy is ±5% at 90% confidence limits.

Table 12. DD-964 Longitudinal Forces and Coefficients

Test No.	Environmental Excitations: Current Speed (ft/sec)	Current Direction[a]	Wind Speed (ft/sec)	Wind Relative Direction[b] (deg)	Propeller Pitch[c] (%/deg)	Horizontal Mooring Force[d] (klb)	Longitudinal Wind Force (klb)	Longitudinal Current Force (klb)	K[e]
08	2.6	Ebb	24.0	235	0	-3.8	-0.8	4.6	680
09A	1.8	Ebb	22.0	245	0	-3.2	-0.7	3.9	1200
09B	1.3	Ebb	22.0	245	0	-2.9	-0.7	3.6	2130
10	0.9	Flood	15.0	60	0	-2.8	0.8	2.0	2470
1	2.7	Flood	15.0	60	0	-8.6	0.8	7.8	1070
2	3.0	Flood	13.5	60	100/26	-9.15	0.65	8.4	930
3	2.9	Flood	12.0	60	0	-8.3	0.5	7.8	930
5	2.8	Flood	14.0	60	0	-6.2	0.7	5.5	702
6	2.6	Flood	15.0	60	100/26	-5.6	0.8	4.8	710
7	4.9	Ebb	12.0	240	0	-12.9	-0.2	13.1	545
8	4.6	Ebb	13.0	265	100/26	-12.35	-0.25	12.6	595

[a]Flood tide current measurements are accurate; ebb tide measurements are approximate only.

[b]Measured counterclockwise from the bow (head wind = 0 deg angle).

[c]Variable pitch propellers were adjusted as a design parameter. Also, full right-rudder was used for the last two tests.

[d]Positive forces defined in Figure 10.

[e]See Equation 5.

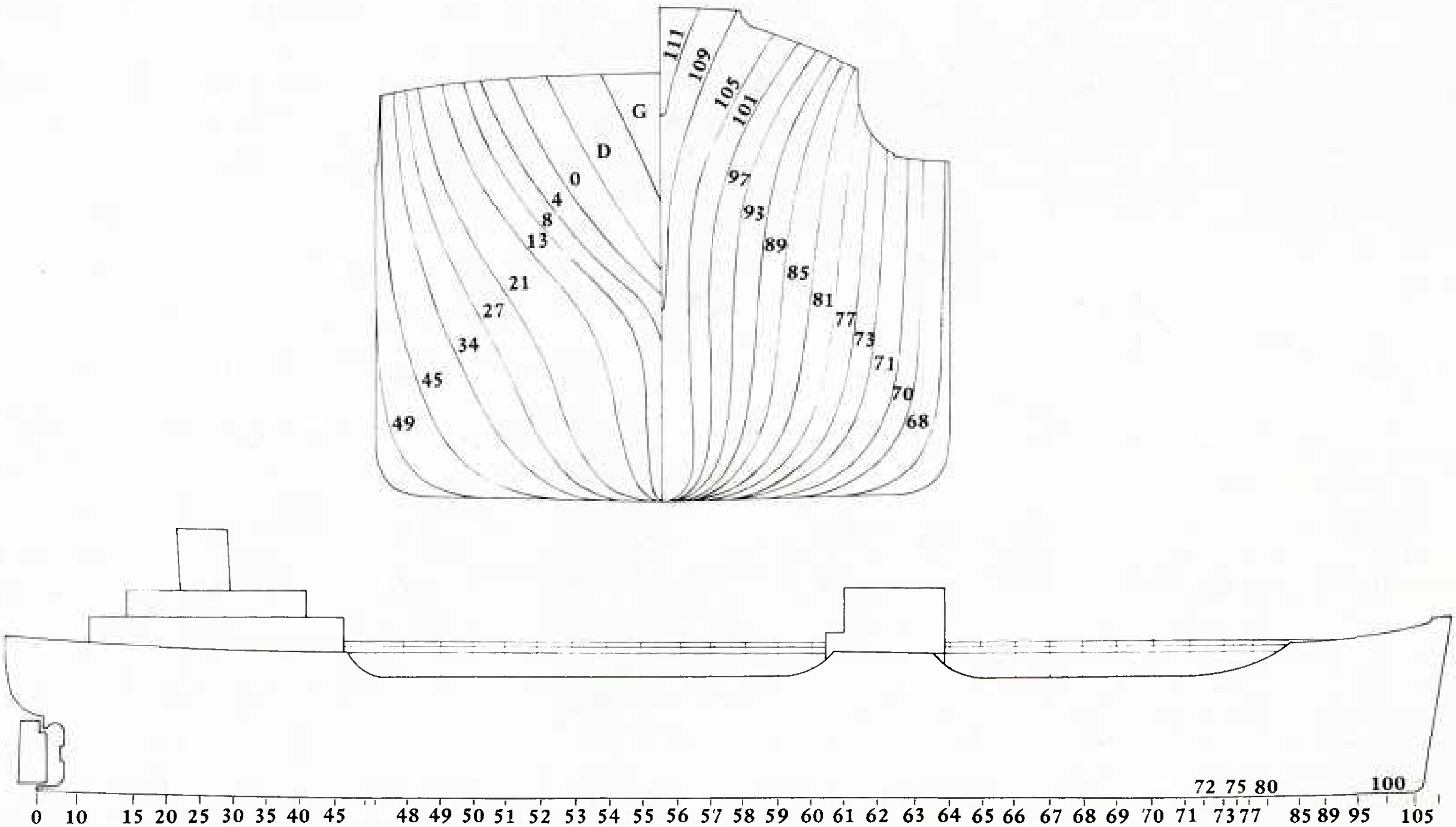


Figure 1. T-2 hull.

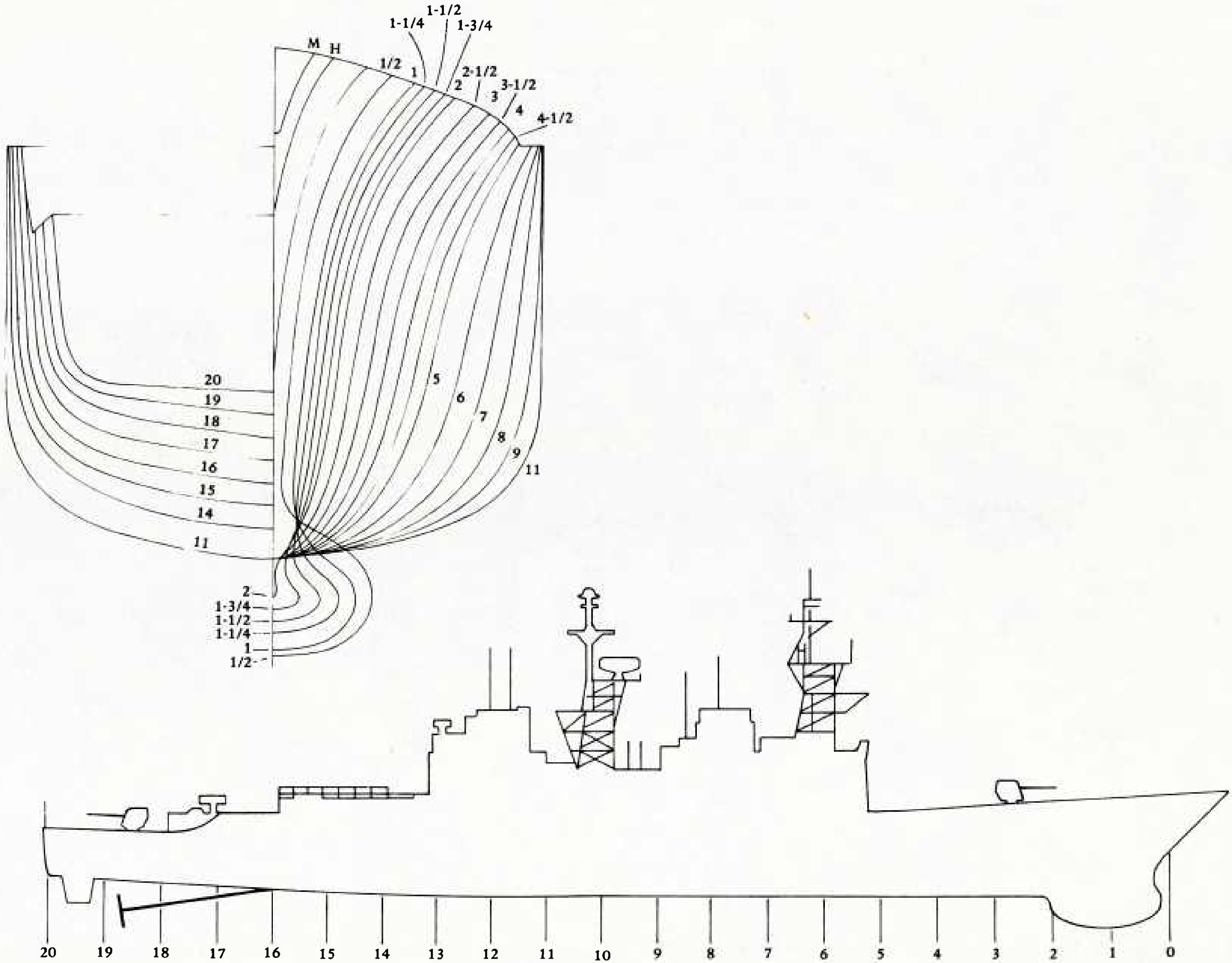


Figure 2. Spruance hull.

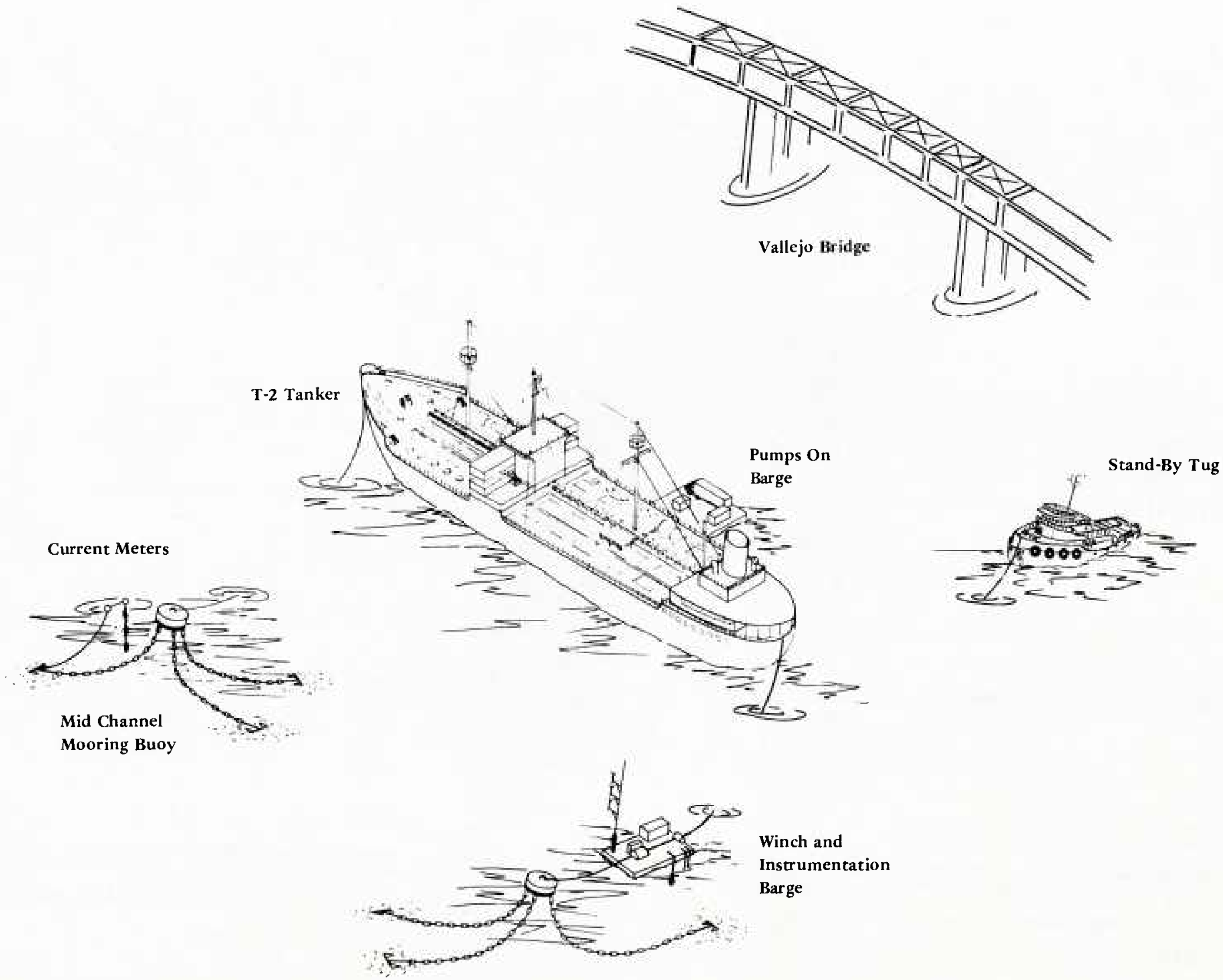


Figure 3. Diagram of test configuration.

Figure 4. Typical test configuration.

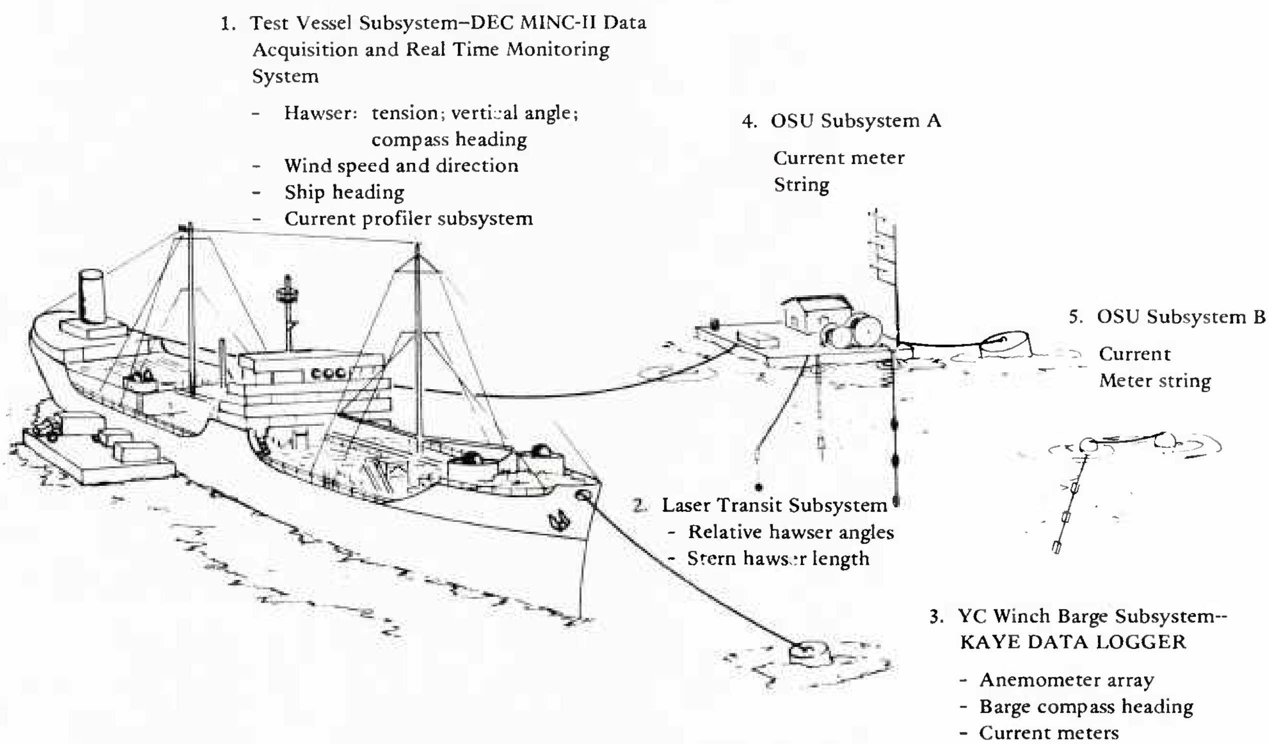


Figure 5. Instrumentation subsystems.

Figure 6. YC barge.

Figure 7. T-2, full draft.

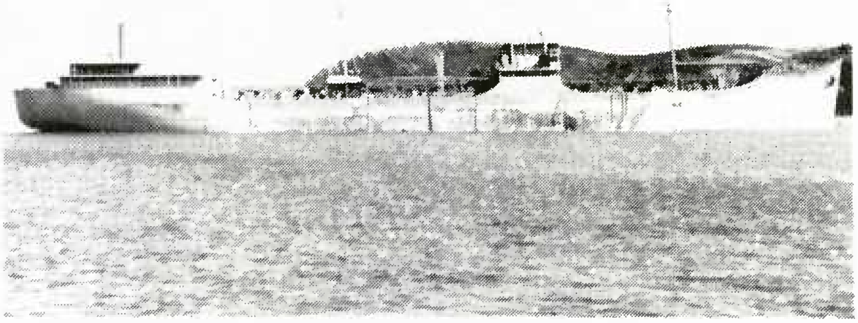
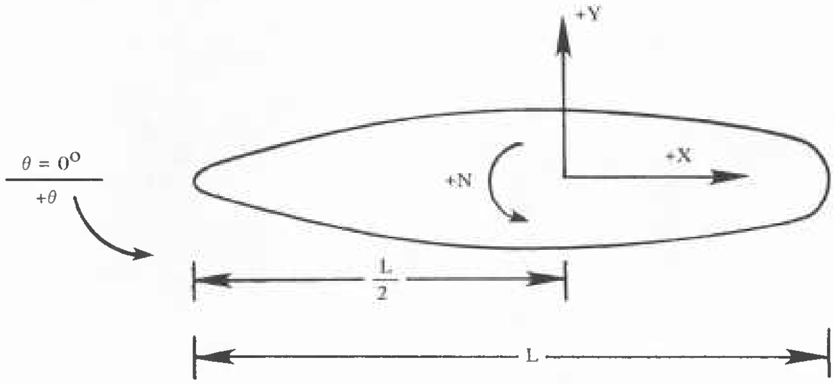
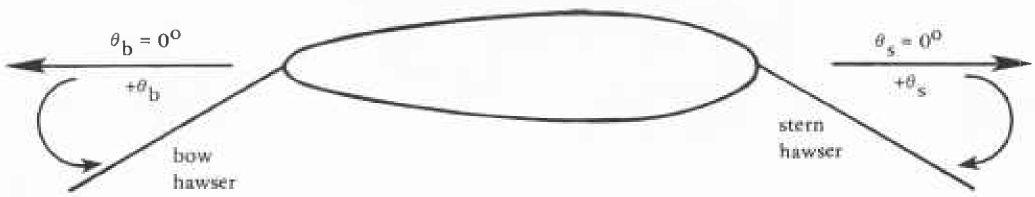


Figure 8. T-2, light draft.

Figure 9. DD-964 on-site.



(a) External loads.



(b) Hawser loads.

Figure 10. Definitions of loads.

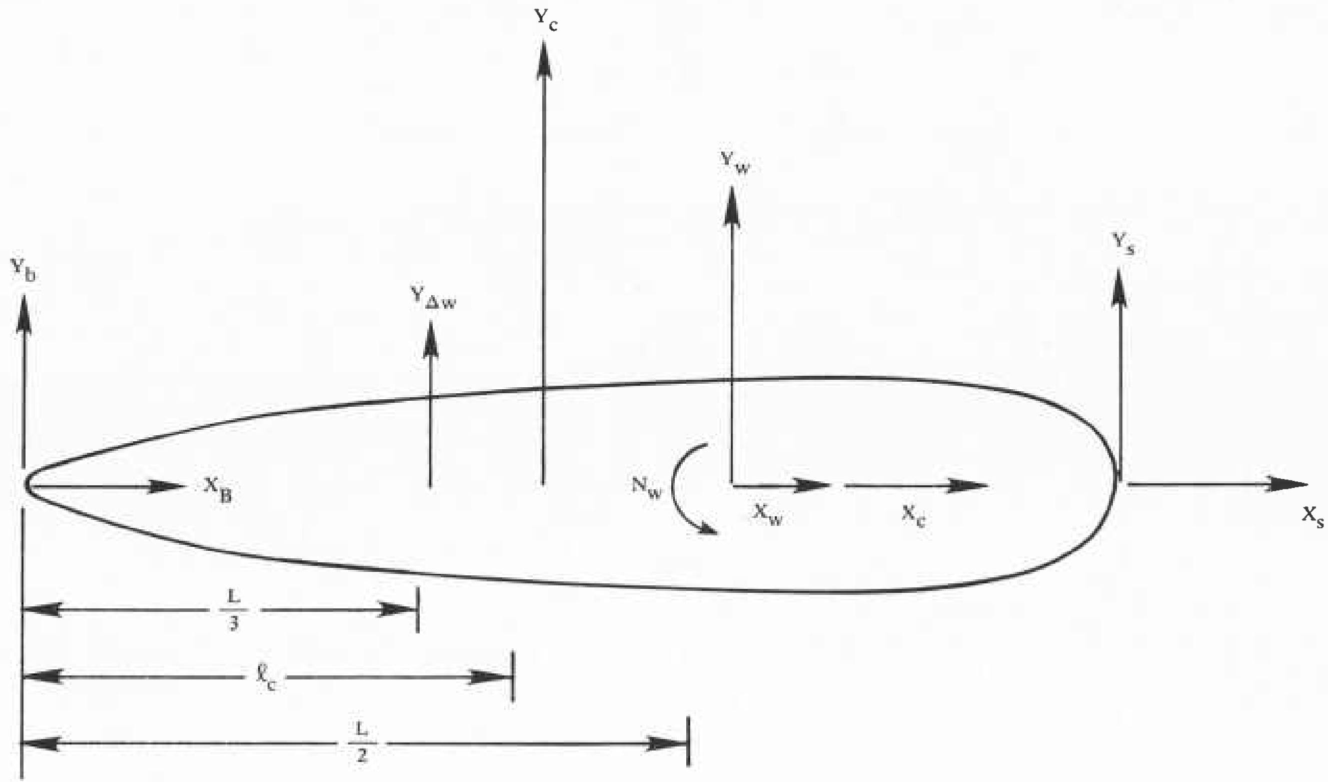


Figure 11. Free-body diagram of system forces.

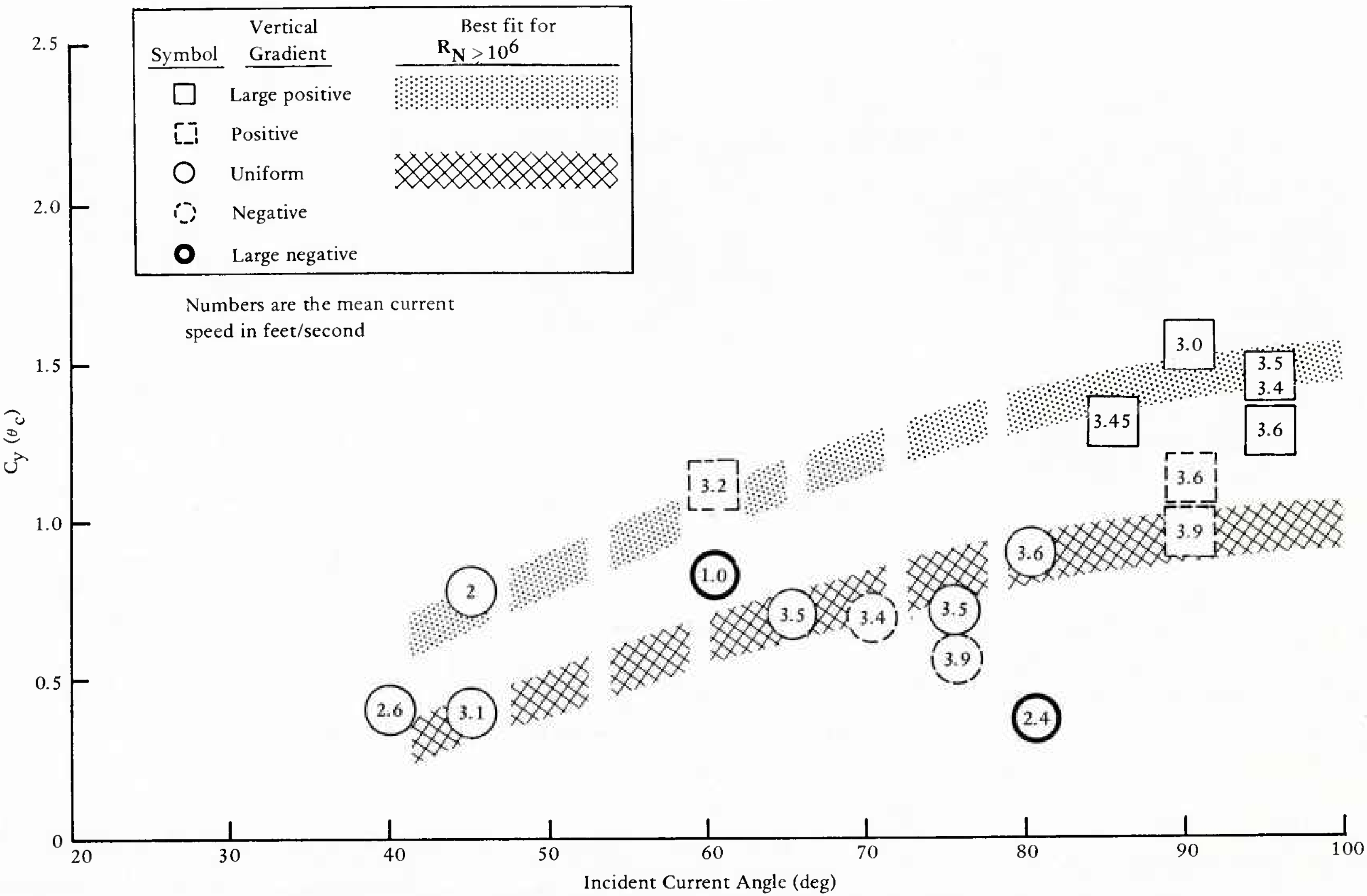


Figure 12. T-2 lateral force coefficients versus incident angle and vertical shear.

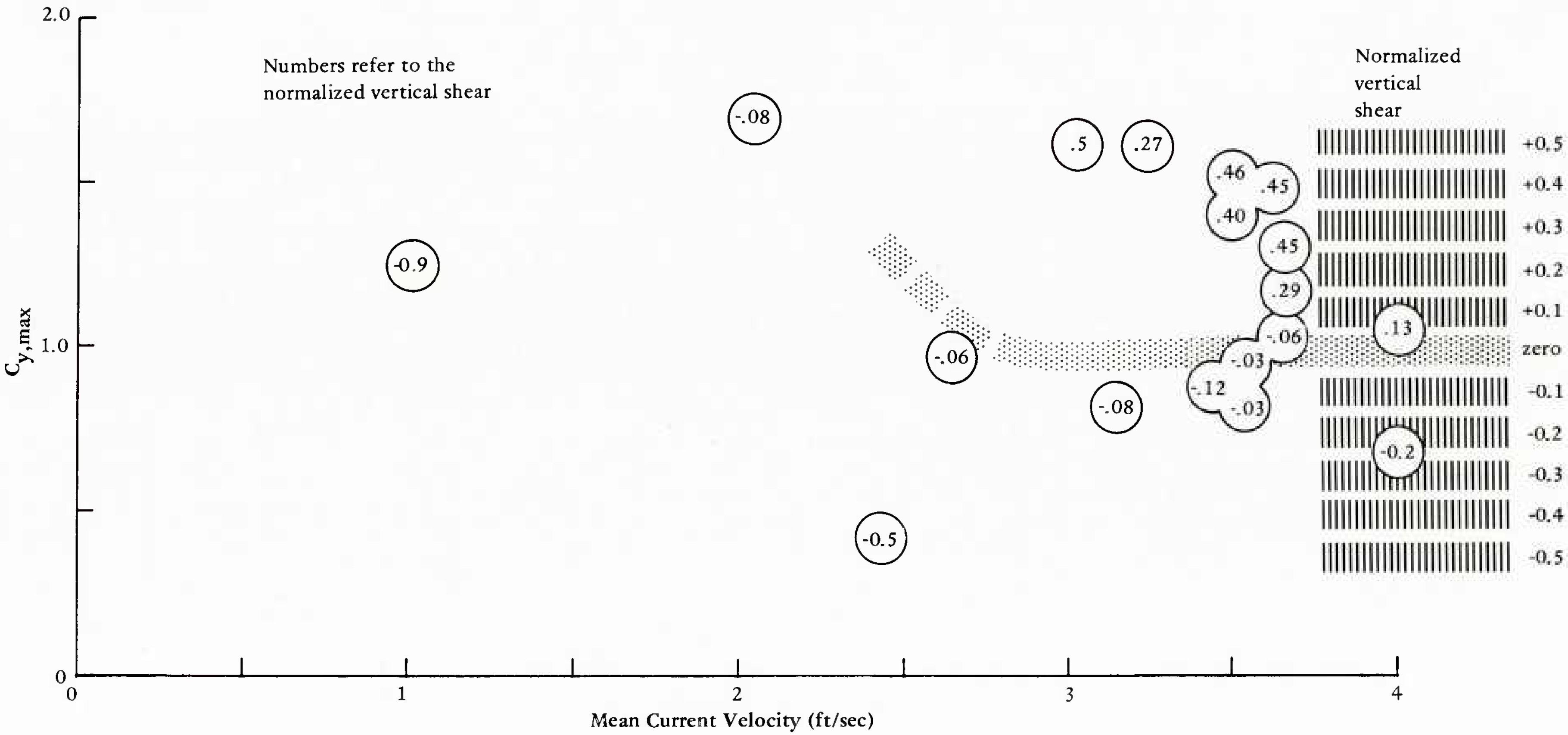


Figure 13. T-2 lateral force coefficients versus current velocity and vertical shear.

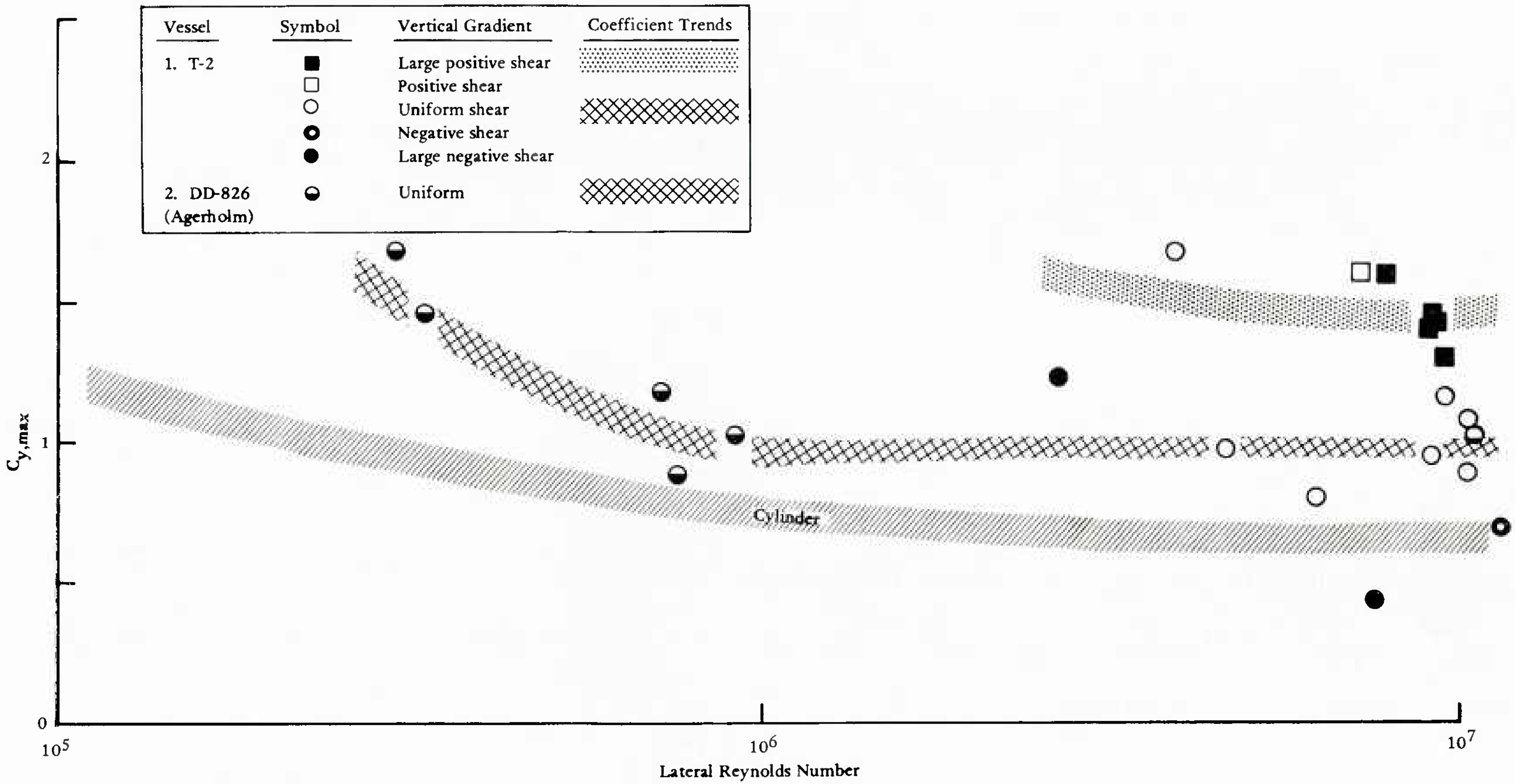


Figure 14. T-2 deep water lateral force coefficients versus Reynolds Number.

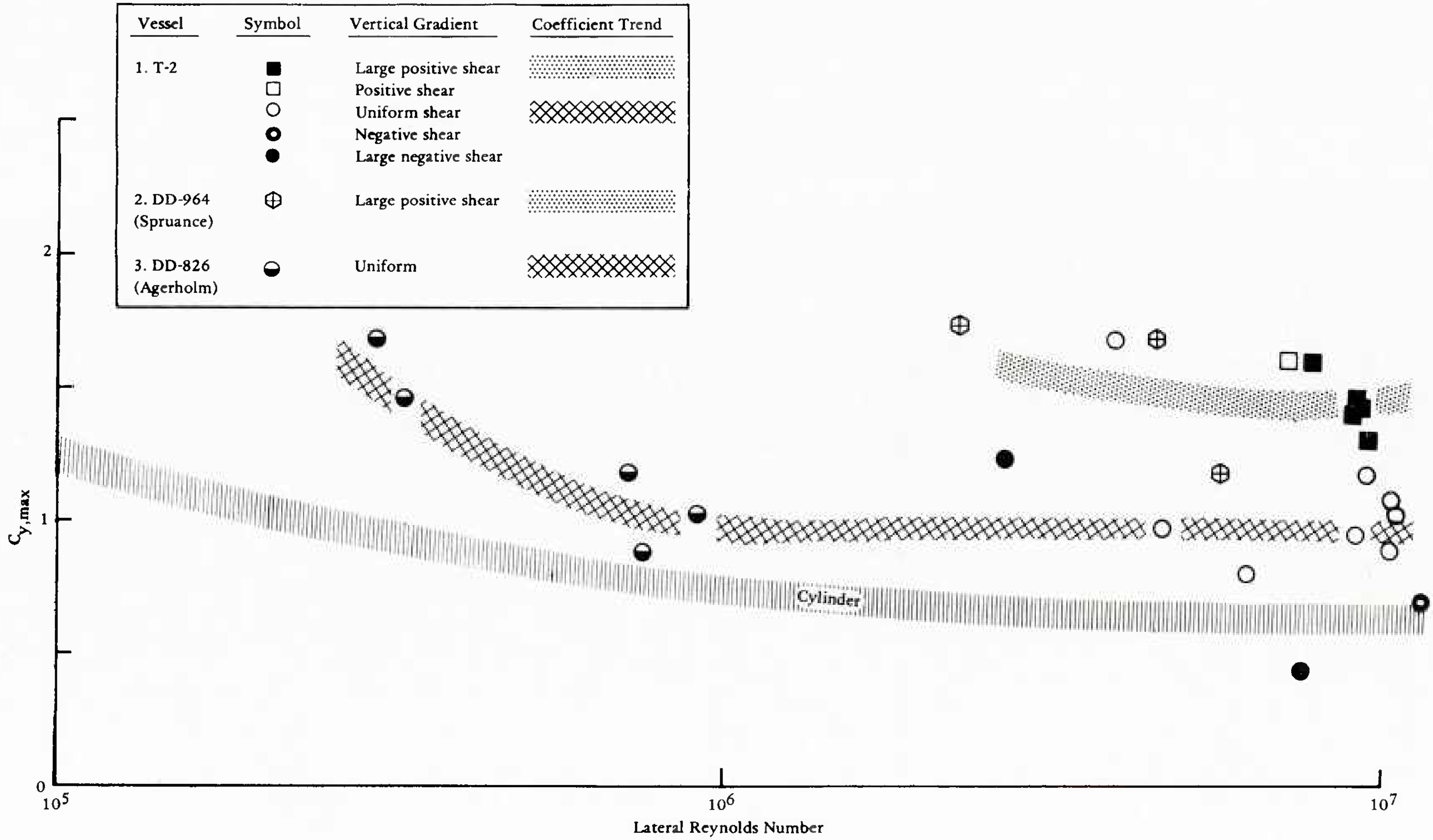


Figure 15. DD-964 lateral force coefficients versus Reynolds Number.

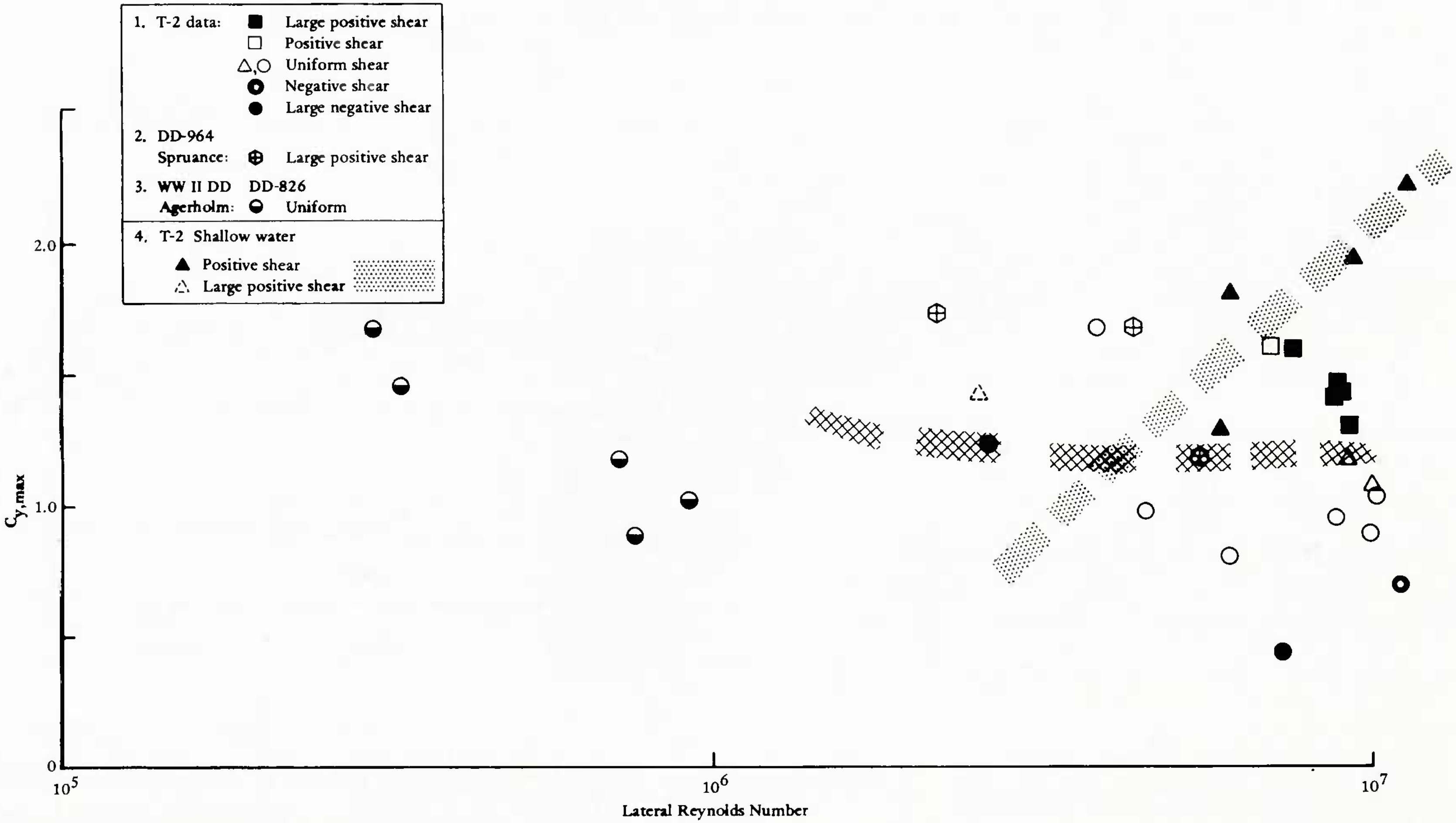


Figure 16. T-2 shallow water lateral force coefficients versus Reynolds Number at water depth/draft = 2.6.

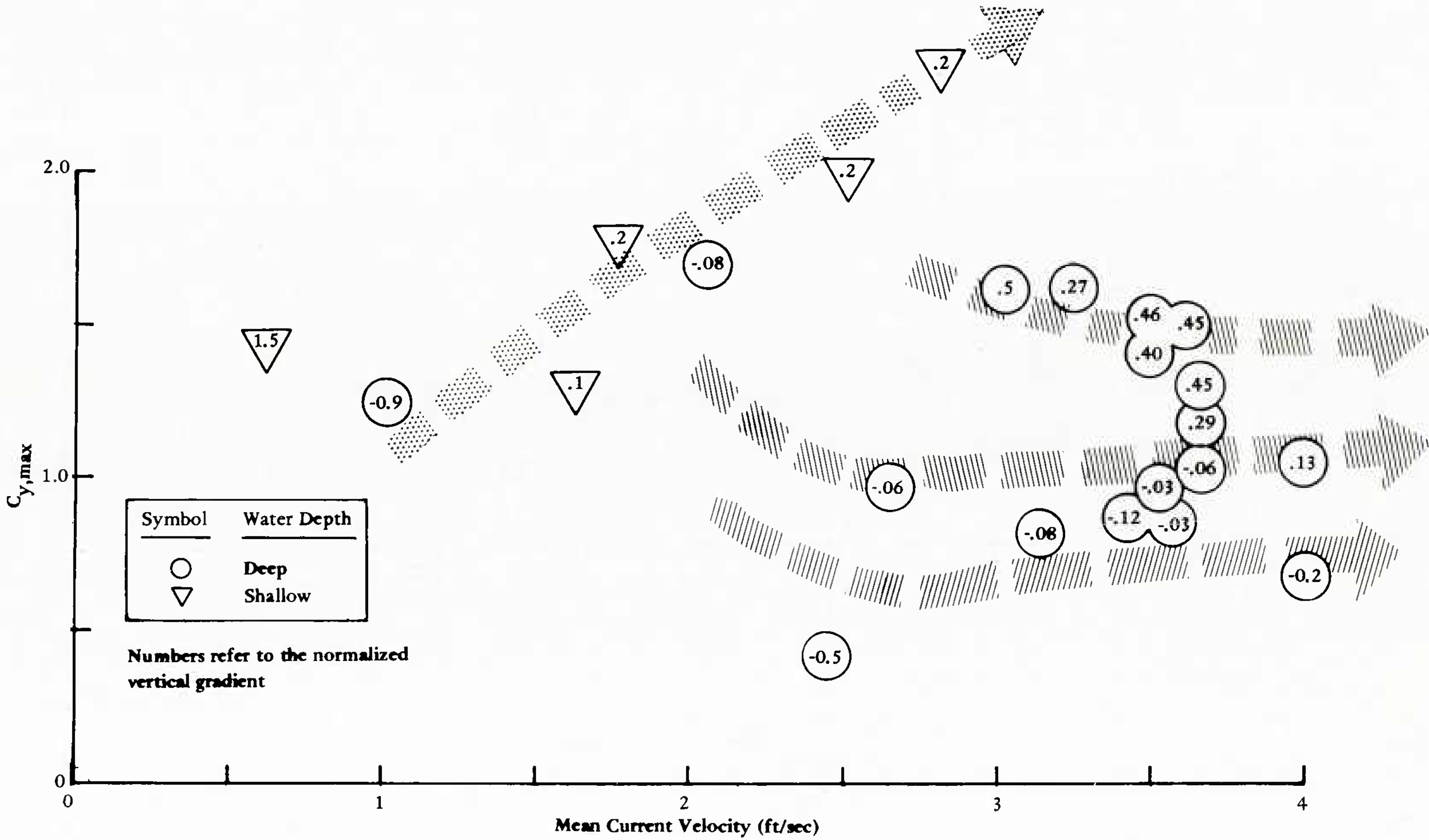


Figure 17. T-2 shallow water lateral force coefficients versus current velocity for water depth/draft = 2.6.

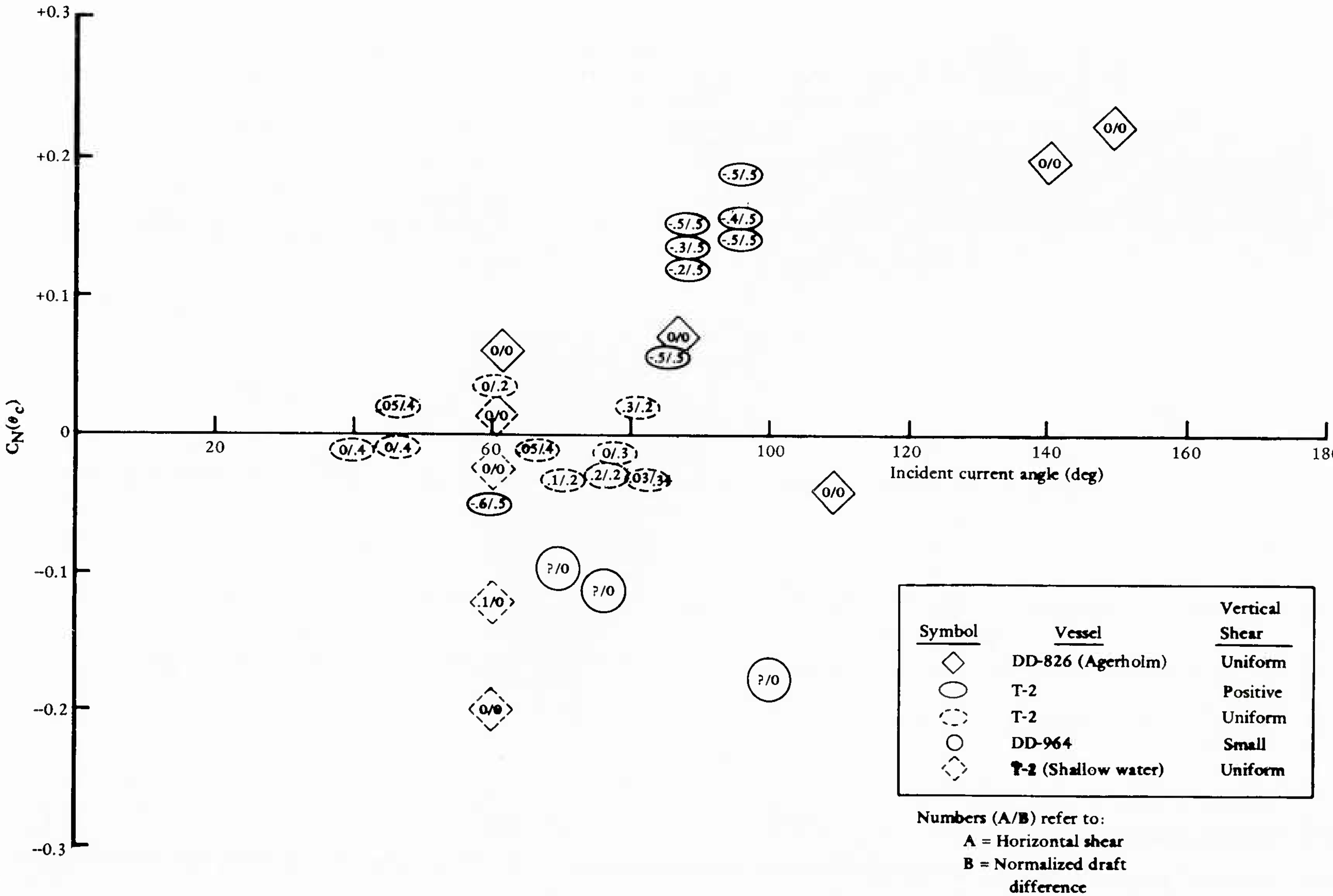


Figure 18. All yaw moment coefficients versus incident angle.

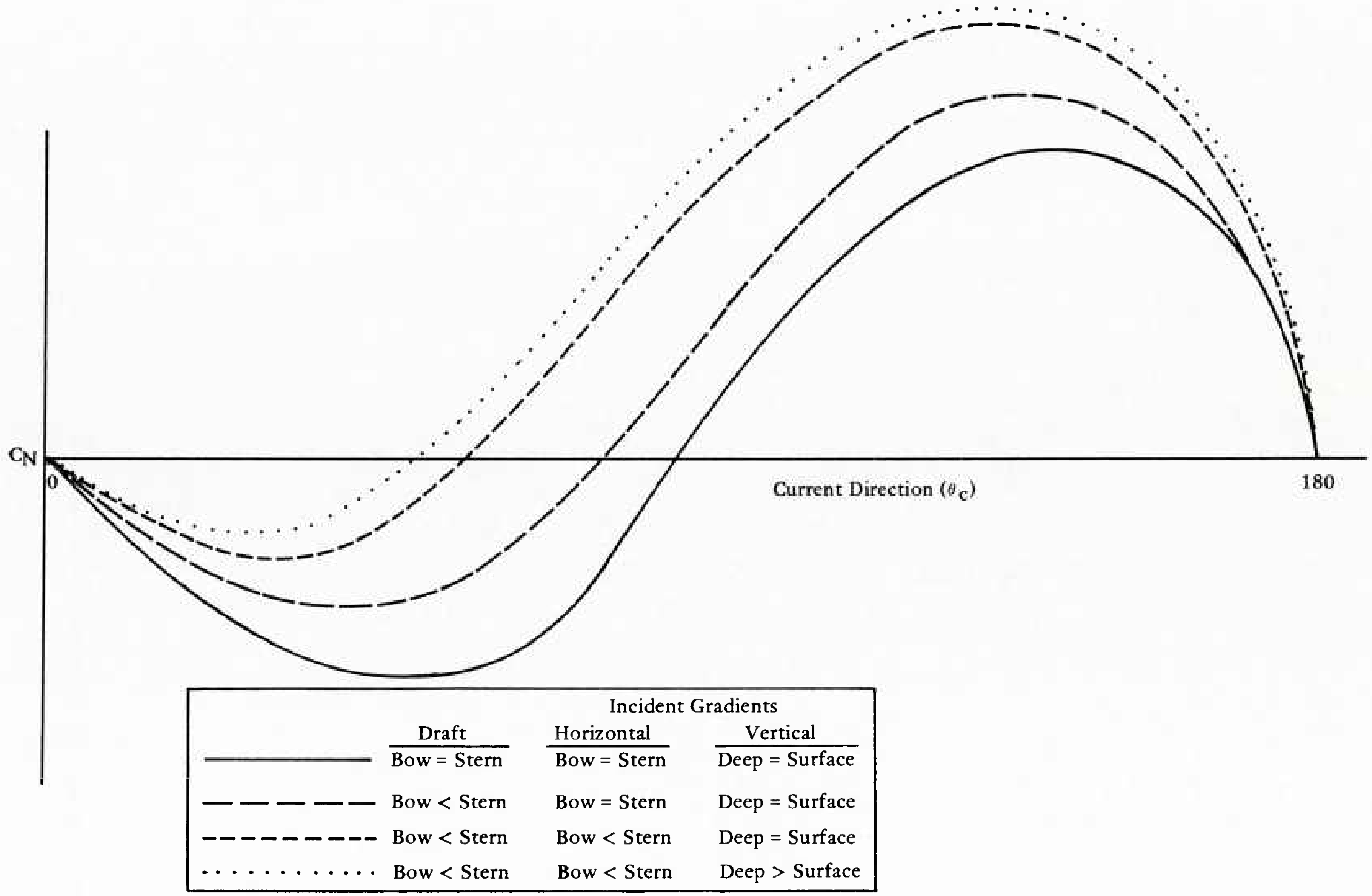


Figure 19. Representative sensitivity of the yaw moment coefficient versus test conditions.

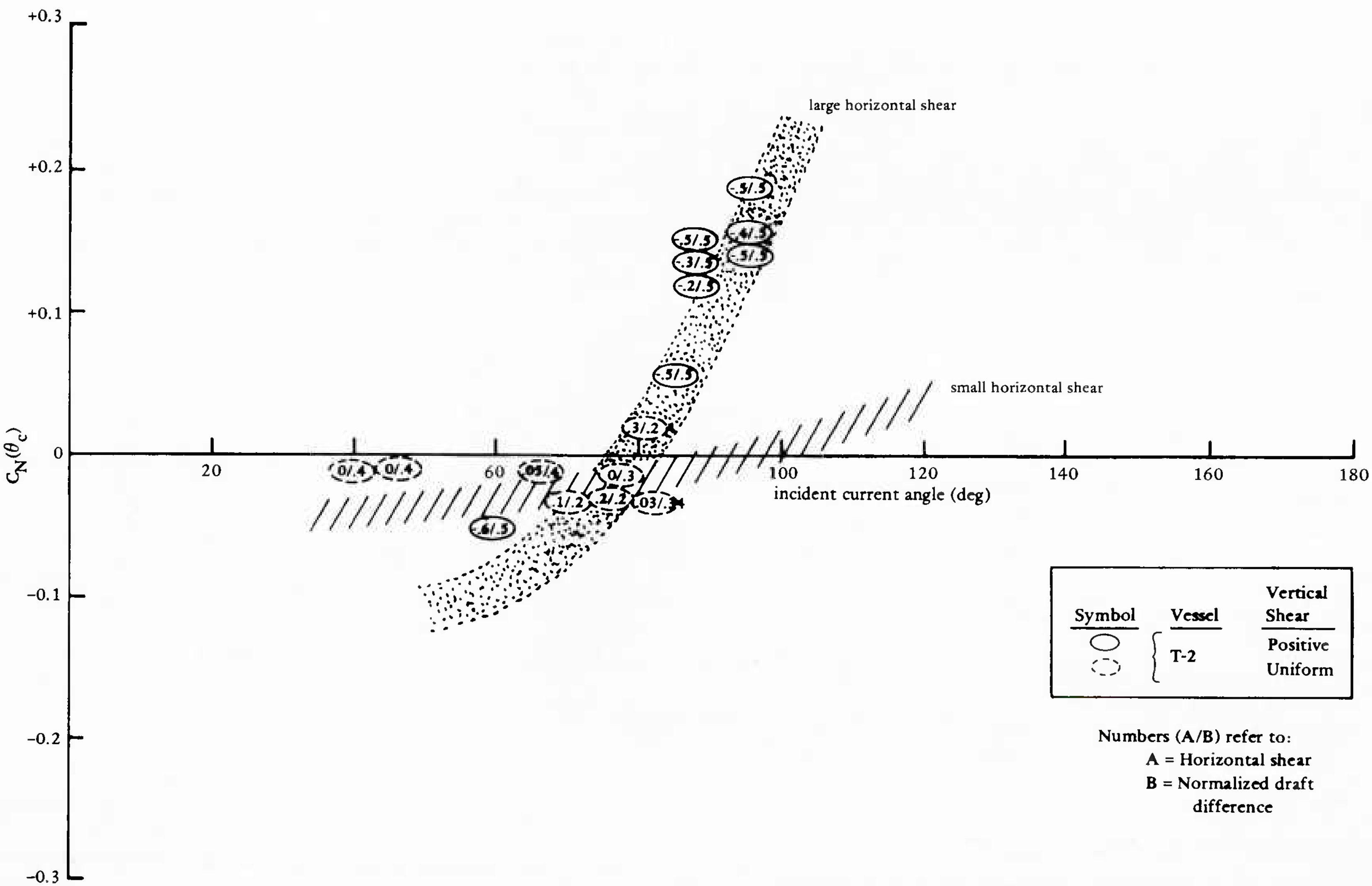


Figure 20. T-2 deep water yaw moment coefficients versus incident angle.

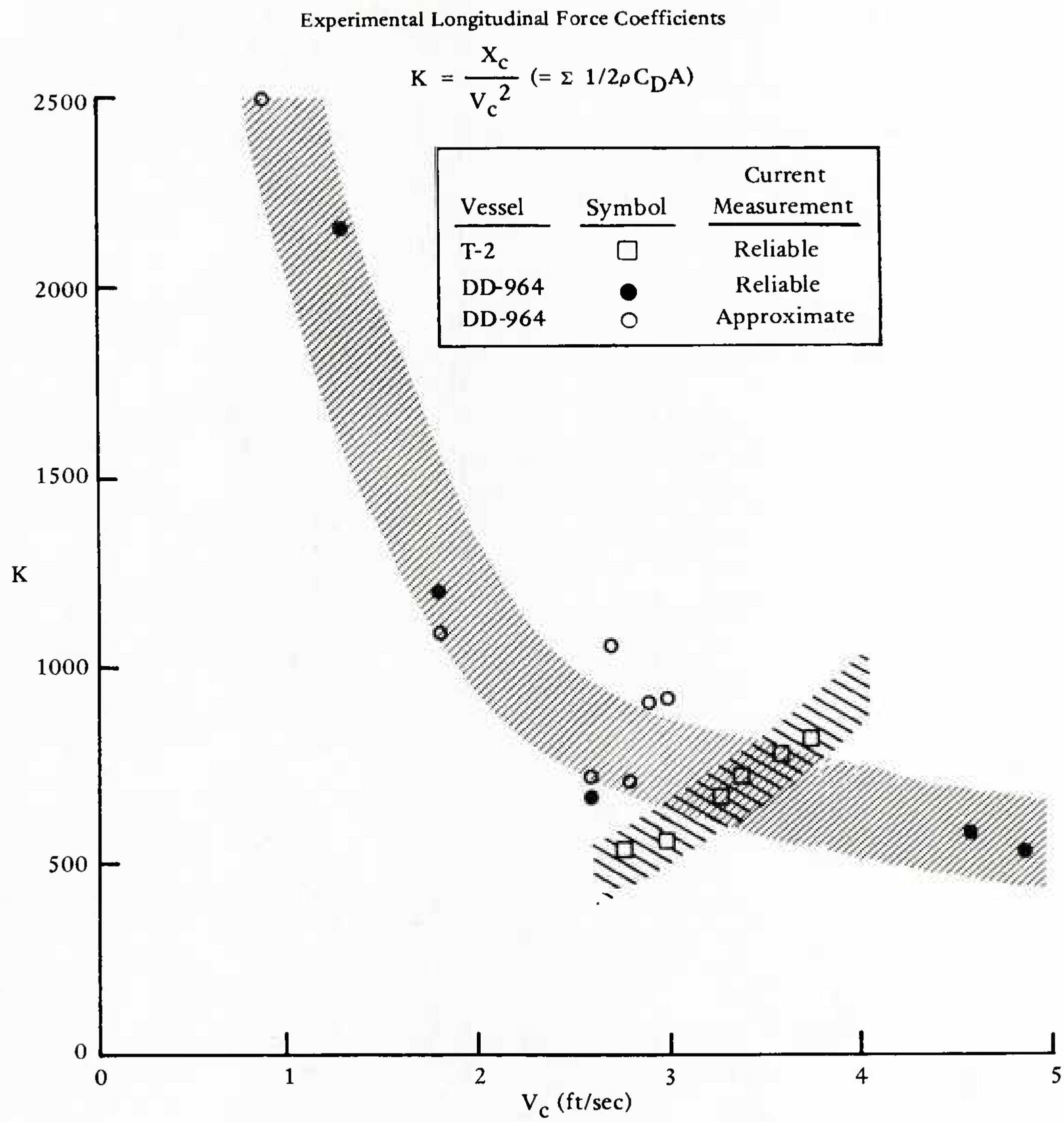


Figure 21. Experimental longitudinal force coefficients versus current velocity.

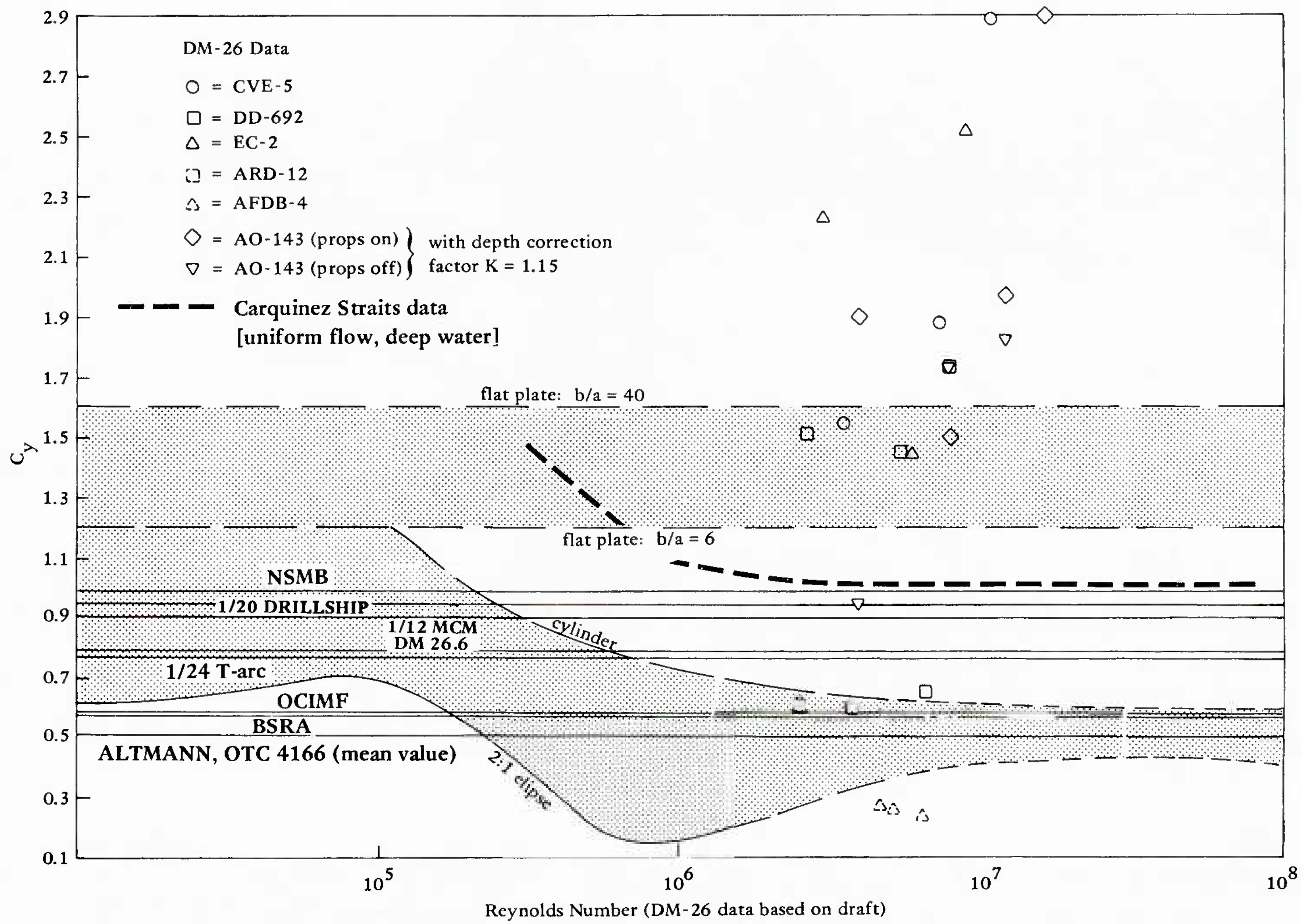


Figure 22. Nondimensional lateral force coefficients versus Reynolds Number.

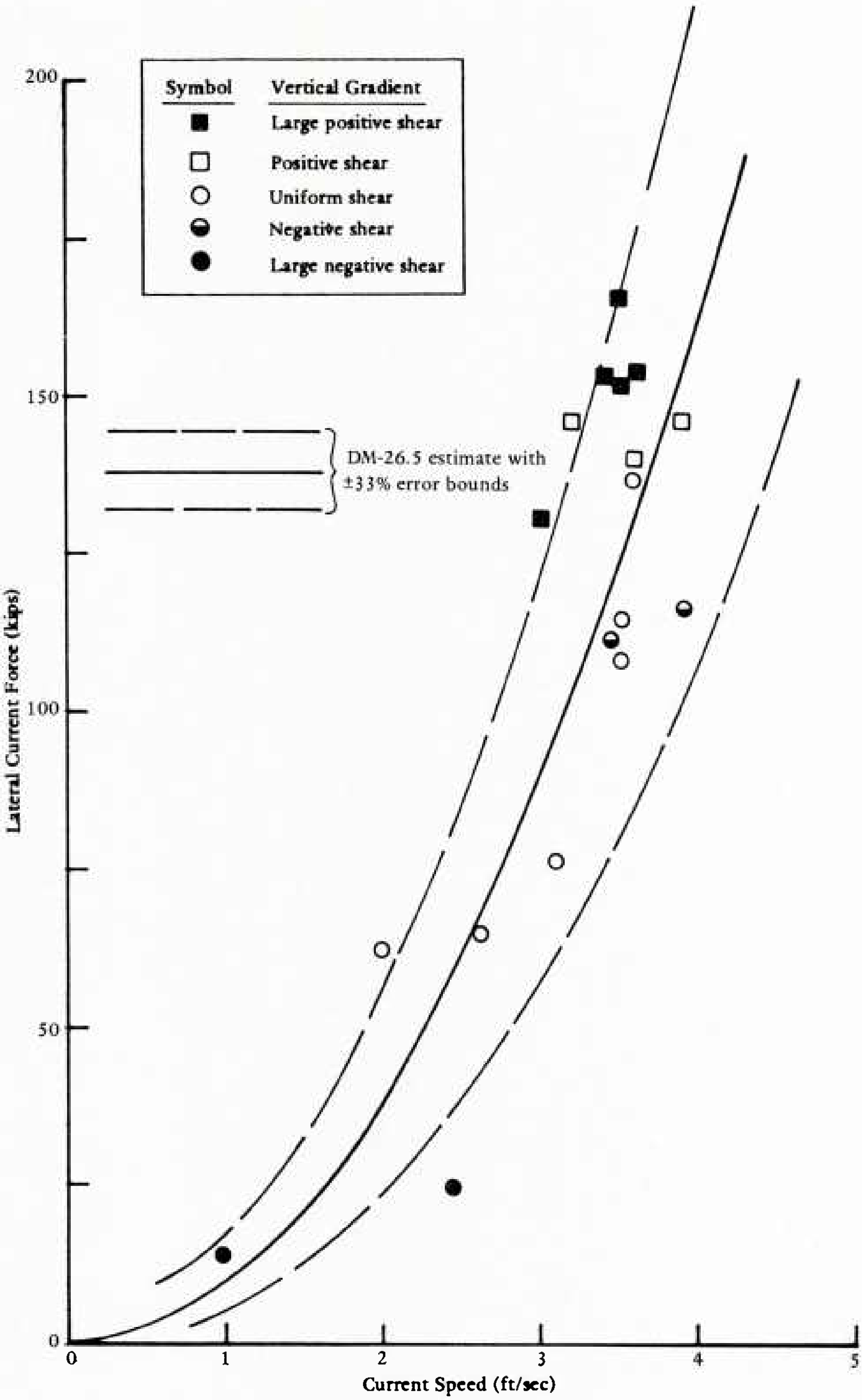


Figure 23. Comparison between measured T-2 lateral forces and DM-26.5 estimates.

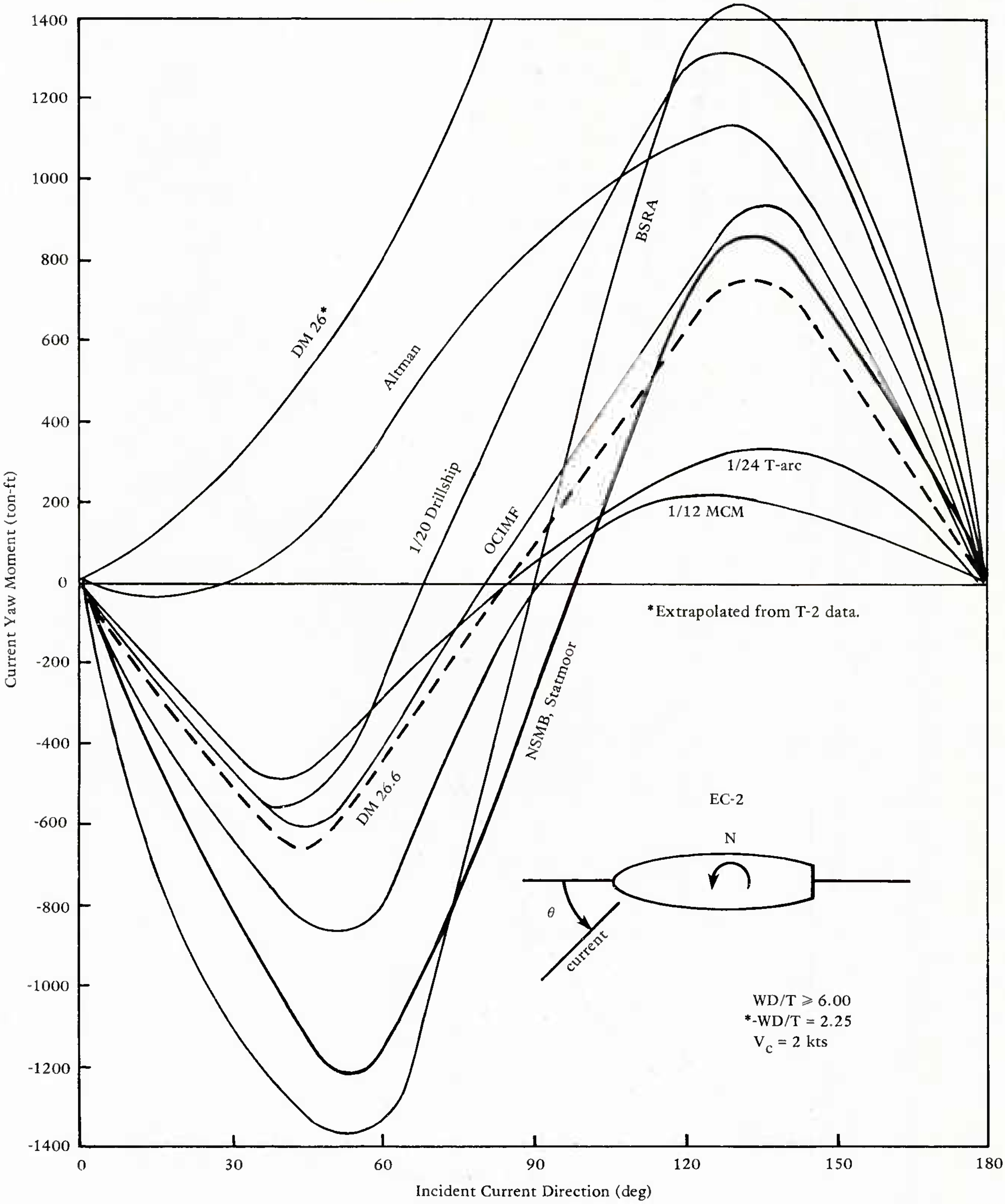


Figure 24. Comparison of state-of-the-art yaw moment prediction methods.

Appendix A

SAMPLE DATA SET

A large number of measurements were required in each test to allow for a complete description of the excitations and system response. Many of these were dynamic in nature, such as wind speed, while some were static, such as the vessel heading and some backup measurements. This appendix contains some of the "dynamic" measurements from test 2501 to illustrate representative data.

Figures A-1 through A-8 show the bow and stern hawser response and wind field measurements for that test. Information on the instrumentation is presented in the INSTRUMENTATION section of the report. Averaged values from these figures used in the analyses are presented in Tables 2a and 2b.

A discussion of the current fields is included in Appendix B. Measurements pertinent to this sample data set (test 2501) are included in that appendix to illustrate a typical current field.

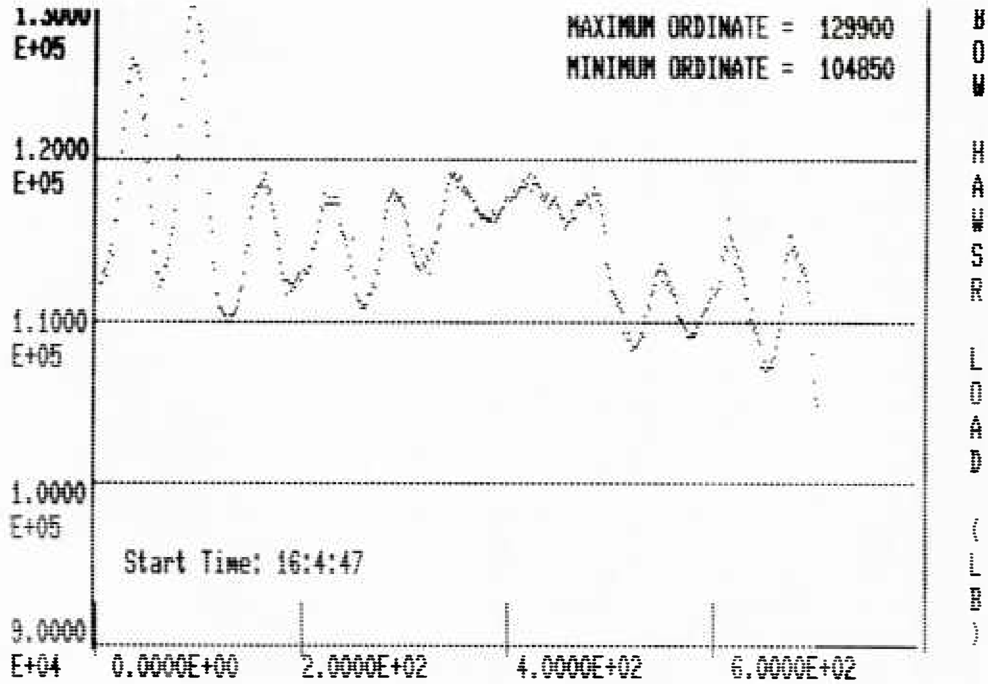


Figure A-1. Bow hawser load versus time, test 2501.

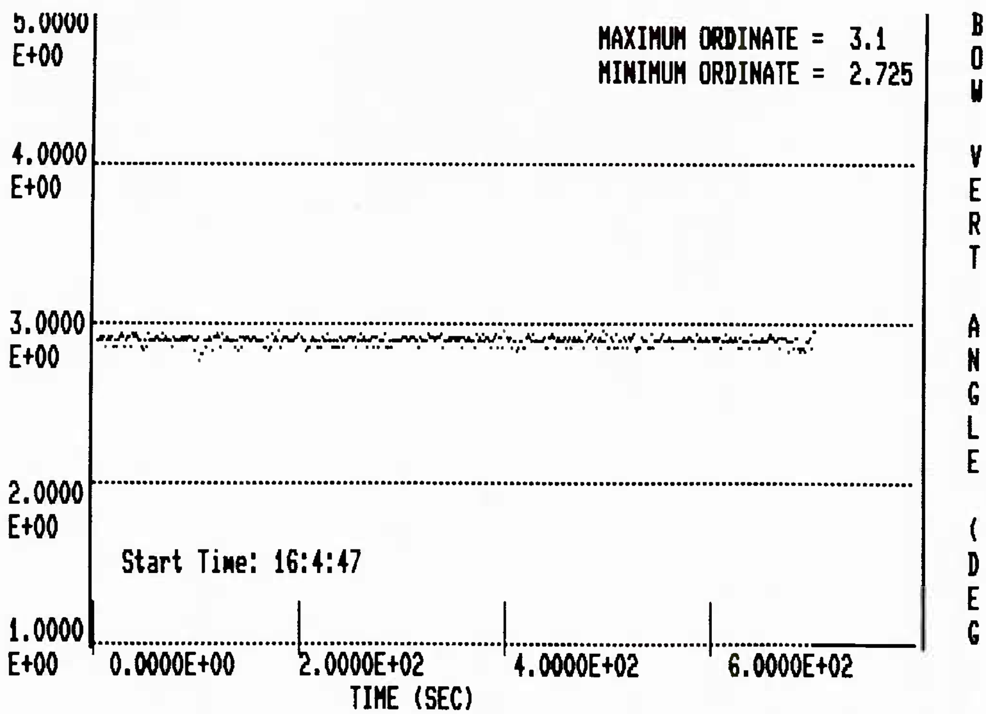


Figure A-2. Bow vertical angle versus time, test 2501.

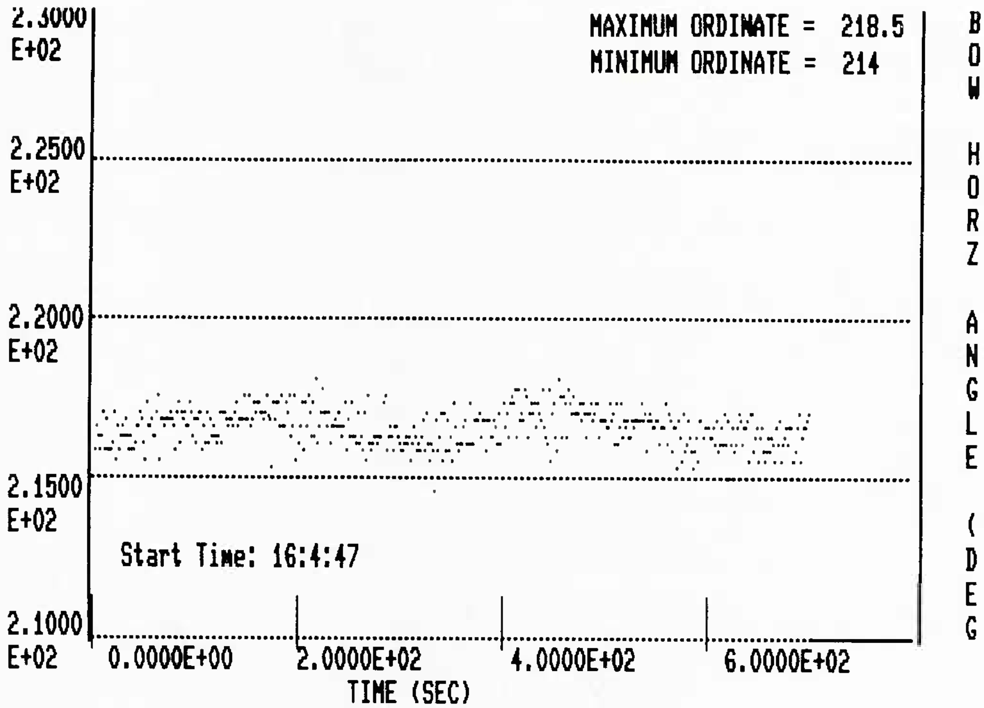


Figure A-3. Bow horizontal angle versus time, test 2501.

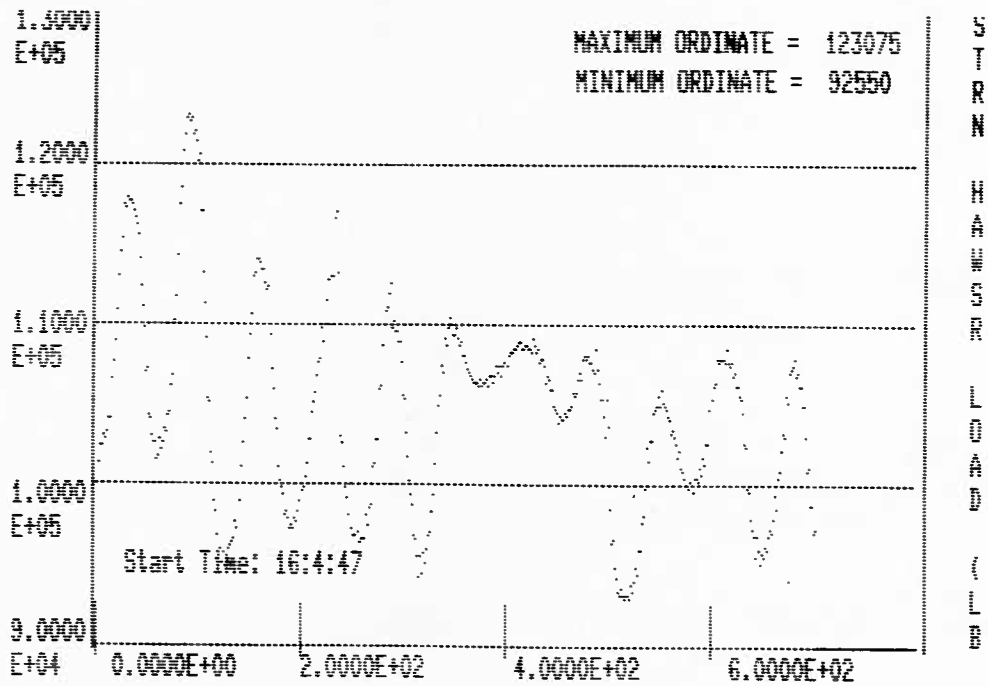


Figure A-4. Stern hawser load versus time, test 2501.

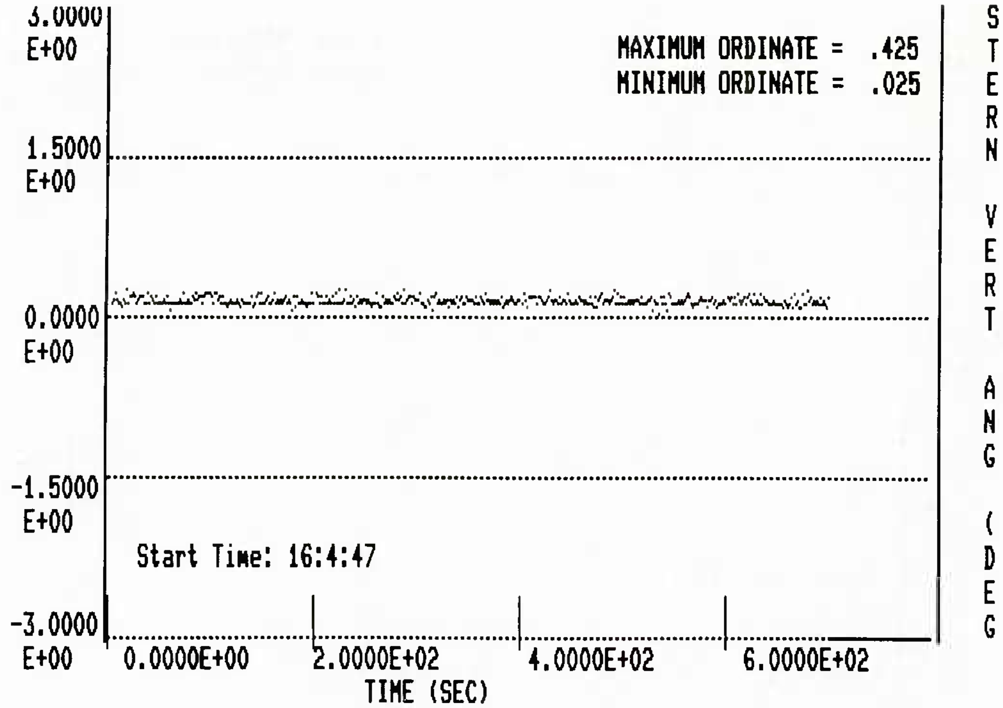


Figure A-5. Stern vertical angle versus time, test 2501.

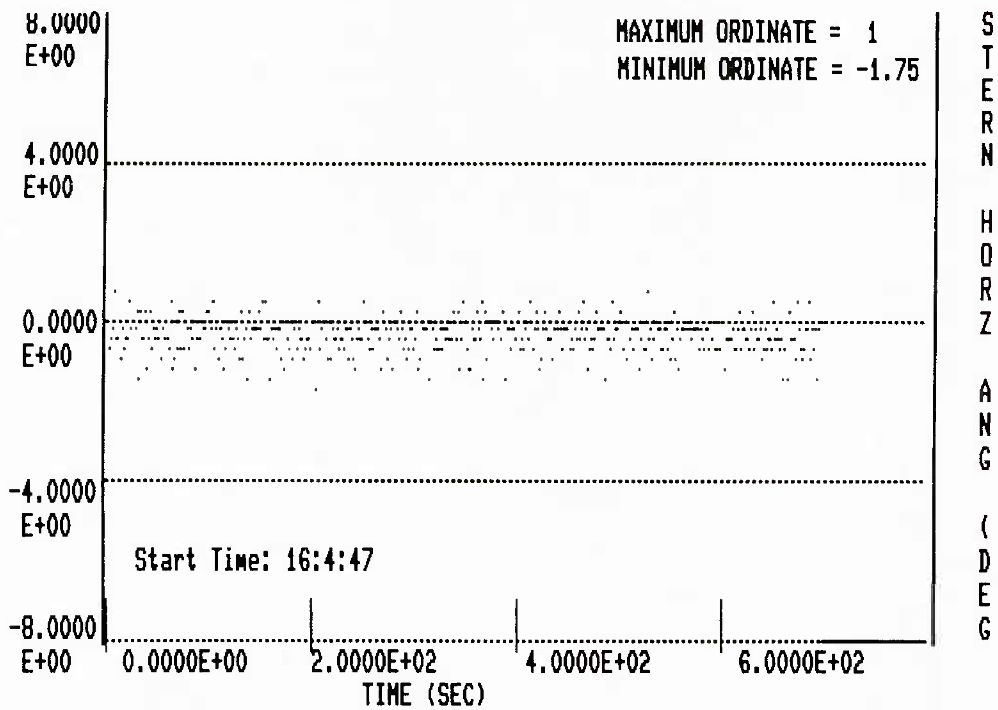


Figure A-6. Stern horizontal angle versus time, test 2501.

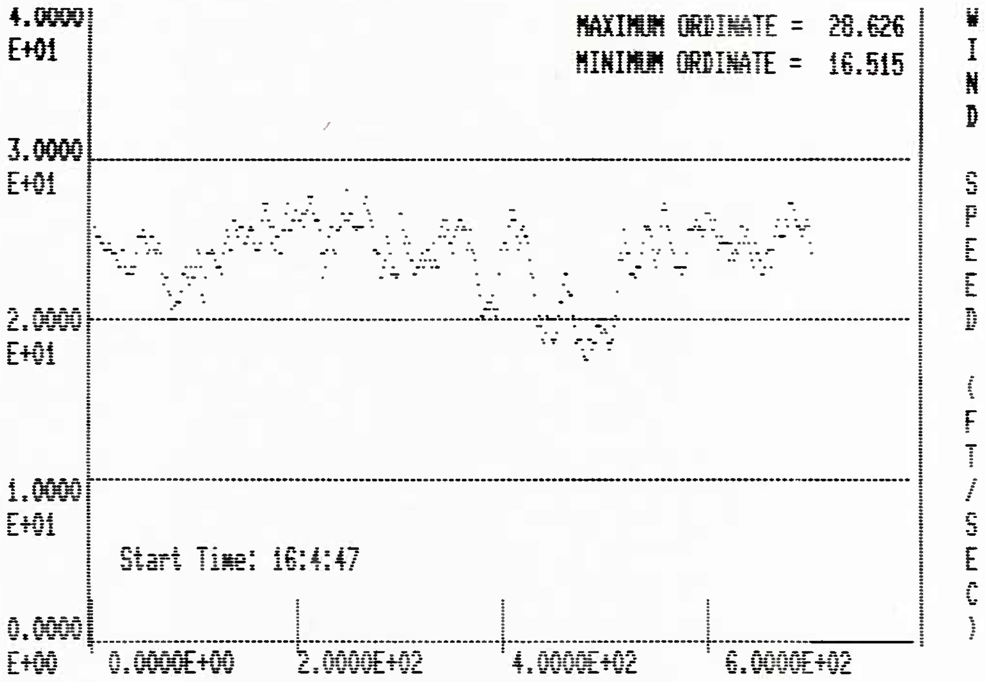


Figure A-7. Wind speed versus time, test 2501.

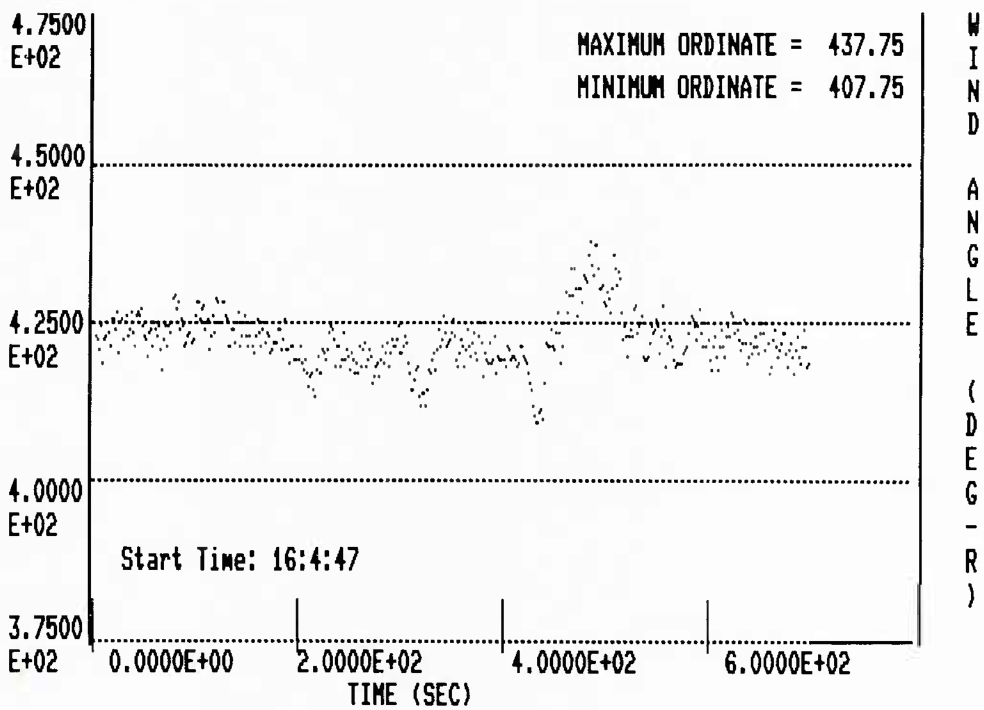


Figure A-8. Wind angle versus time, test 2501.

Appendix B

WIND AND CURRENT EXCITATIONS

Both of these excitations were carefully measured in these tests, including instantaneous, time-averaged, and spatial measurements. Further information is contained in the DATA COLLECTION AND PREPARATION section.

The wind was usually steady and varied between 0 and 36 ft/sec over the course of the T-2 and DD-964 tests. As shown in Figures A-7 and A-8 in Appendix A, the wind was steady over individual tests. In addition, measurements taken at the T-2 and the YC barge were always within 1 ft/sec, typically less than 0.5 ft/sec, which shows that the wind field was very uniform.

Figure B-1 and Tables B-1 and B-2 illustrate the character of the current field over time scales corresponding to individual tests. Data from test 2501 are presented to augment the data in Appendix A. Figure B-1 shows the steady nature of the flow, taken from instantaneous measurements. Tables B-1 and B-2 show both the time and spatial characteristics of the current field over 1 hour, including test 2501.

Current measurements for the T-2 and DD-964 tests are shown in Figures B-2 and B-3, respectively.

Table B-1. Representative 1-Minute Averaged Currents[a]

Time	Current Speed (ft/sec) and Direction (magnetic deg, current towards) at the Following Additional Minutes--																			
	+0		+1		+2		+3		+4		+5		+6		+7		+8		+9	
	Speed	Dir.	Speed	Dir.	Speed	Dir.	Speed	Dir.	Speed	Dir.	Speed	Dir.	Speed	Dir.	Speed	Dir.	Speed	Dir.	Speed	Dir.
Depth = 10 ft[b]																				
1527	2.873	78.0	2.847	83.3	2.998	80.7	2.998	78.8	2.841	80.4	2.837	82.8	2.957	79.2	2.924	82.7	2.942	82.7	2.995	81.7
1537	2.932	82.6	2.984	80.1	2.971	81.6	2.875	85.6	2.879	85.9	2.878	83.1	2.955	82.6	2.856	84.8	2.811	84.6	2.793	83.7
1547	2.749	87.4	2.742	86.9	2.780	81.7	2.769	78.7	2.782	80.3	2.879	83.3	2.774	81.9	2.732	79.7	2.766	81.8	2.813	77.9
1557	2.751	78.6	2.781	78.8	2.748	79.5	2.733	81.2	2.599	79.1	2.610	80.5	2.567	78.5	2.513	78.9	2.510	84.3	2.556	79.8
1607	2.686	82.2	2.603	79.7	2.600	82.7	2.616	81.6	2.587	78.4	2.691	77.2	2.666	75.8	2.662	80.3	2.621	81.0	2.635	78.7
1617	2.635	76.8	2.700	76.4	2.697	77.5	2.528	76.9	2.618	77.5	2.564	77.4	2.612	79.1	2.495	75.2	2.550	78.8	2.535	78.5
1627	2.346	77.1	2.499	76.2	2.524	79.5	2.452	74.9	2.394	74.3	2.552	76.9	2.421	79.7	2.358	76.3	2.281	76.6	2.321	78.3
1637	2.295	74.6	2.346	79.0	2.313	81.1	2.299	75.1	2.345	79.8	2.400	79.1	2.360	79.1	2.415	77.0	2.405	78.1	2.221	76.8
Depth = 30 ft[c]																				
1521	3.638	86.7	3.760	88.4	3.637	91.3	3.641	93.0	3.472	92.6	3.498	92.2	3.604	89.9	3.507	91.9	3.546	89.2	3.433	88.7
1531	3.573	89.0	3.570	91.9	3.664	89.3	3.465	91.3	3.491	90.1	3.614	90.8	3.368	92.6	3.465	91.3	3.410	91.1	3.454	92.5
1541	3.424	93.8	3.410	92.2	3.562	91.3	3.445	93.4	3.409	95.3	3.467	91.0	3.457	90.5	3.408	88.7	3.412	90.5	3.461	92.6
1551	3.498	92.1	3.470	91.8	3.389	93.4	3.397	88.9	3.310	90.5	3.298	91.9	3.384	93.3	3.341	94.0	3.198	91.5	3.271	91.8
1601	3.274	90.9	3.231	92.1	3.172	92.0	3.181	92.1	3.201	92.8	3.233	89.5	3.158	93.8	3.239	93.4	3.130	91.4	2.993	90.4
1611	2.975	87.6	2.938	88.2	3.187	93.6	3.186	93.4	3.128	91.8	3.245	93.3	3.131	90.2	3.224	92.3	3.226	94.2	3.086	93.1
1621	3.149	93.6	3.166	94.4	2.955	92.2	3.064	92.4	2.903	89.1	2.867	91.5	2.945	94.9	3.014	92.5	3.068	94.9	2.920	93.1
1631	2.871	93.3	2.713	90.6	2.880	90.8	2.910	92.6	2.906	95.4	2.843	94.3	2.563	90.6	2.672	90.2	2.649	89.8	2.717	91.1
1641	2.643	88.3	2.455	84.1	2.366	84.7	2.612	84.7	2.479	80.7	2.335	79.7	2.364	77.8	2.472	74.6	2.612	71.9	2.546	67.2

[a]See Table 2a for average current values used in analysis.

[b]Test 2501 runs from 1557 +5 through 1607 +9.

[c]Test 2501 runs from 1601 +1 through 1611 +5.

Table B-2. Representative 5-Minute Averaged Currents

Time	Depth = 10 ft				Depth = 30 ft				Velocity (ft/sec) and Direction (magnetic deg) Differences (Shallow Minus Deep)			
	Average Velocity (ft/sec)			Direction (magnetic deg)	Average Velocity (ft/sec)			Direction (magnetic deg)				
	East	North	Total		East	North	Total		East	North	Total	Direction
1527	2.868	0.494	2.910	80.2	3.517	-0.023	3.517	90.3	-0.649	0.517	-0.607	-10
1532	2.900	0.418	2.930	81.8	3.552	-0.020	3.552	90.3	-0.652	0.438	-0.622	-8
1537	2.905	0.352	2.926	83.0	3.460	-0.099	3.462	91.6	-0.555	0.451	-0.536	-9
1542	2.842	0.310	2.858	83.7	3.444	-0.192	3.449	93.1	-0.602	0.502	-0.591	-9
1547	2.738	0.338	2.759	82.9	3.440	-0.039	3.440	90.6	-0.702	0.377	-0.681	-8
1552	2.756	0.439	2.791	80.9	3.411	-0.081	3.412	91.3	-0.655	0.520	-0.621	-10
1557	2.676	0.499	2.722	79.4	3.295	-0.144	3.298	92.5	-0.619	0.643	-0.576	-14
1602[a]	2.514	0.425	2.530	80.4	3.210	-0.111	3.212	91.9	-0.696	0.536	-0.662	-12
1607[a]	2.585	0.413	2.617	80.9	3.148	-0.095	3.149	91.7	-0.563	0.508	-0.532	-11
1612[a]	2.601	0.526	2.653	78.5	3.079	-0.055	3.080	91.0	-0.478	0.581	-0.447	-12
1617[a]	2.568	0.592	2.636	77.0	3.178	-0.146	3.181	92.6	-0.610	0.738	-0.545	-16
1622	2.493	0.538	2.551	77.8	3.043	-0.128	3.046	92.4	-0.550	0.666	-0.495	-14
1627	2.373	0.574	2.442	76.4	2.957	-0.176	2.962	93.4	-0.584	0.750	-0.520	-17
1632	2.330	0.514	2.386	77.5	2.852	-0.127	2.855	92.5	-0.522	0.641	-0.469	-15
1637	2.266	0.485	2.317	77.9	2.687	-0.059	2.688	91.2	-0.421	0.544	-0.371	-13
1642	2.308	0.490	2.360	78.0	2.498	0.237	2.509	84.5	-0.190	0.253	-0.149	-7
1647	2.240	0.537	2.304	76.5	2.364	0.674	2.459	74.0	-0.124	0.137	-0.155	3

[a]Test 2501.

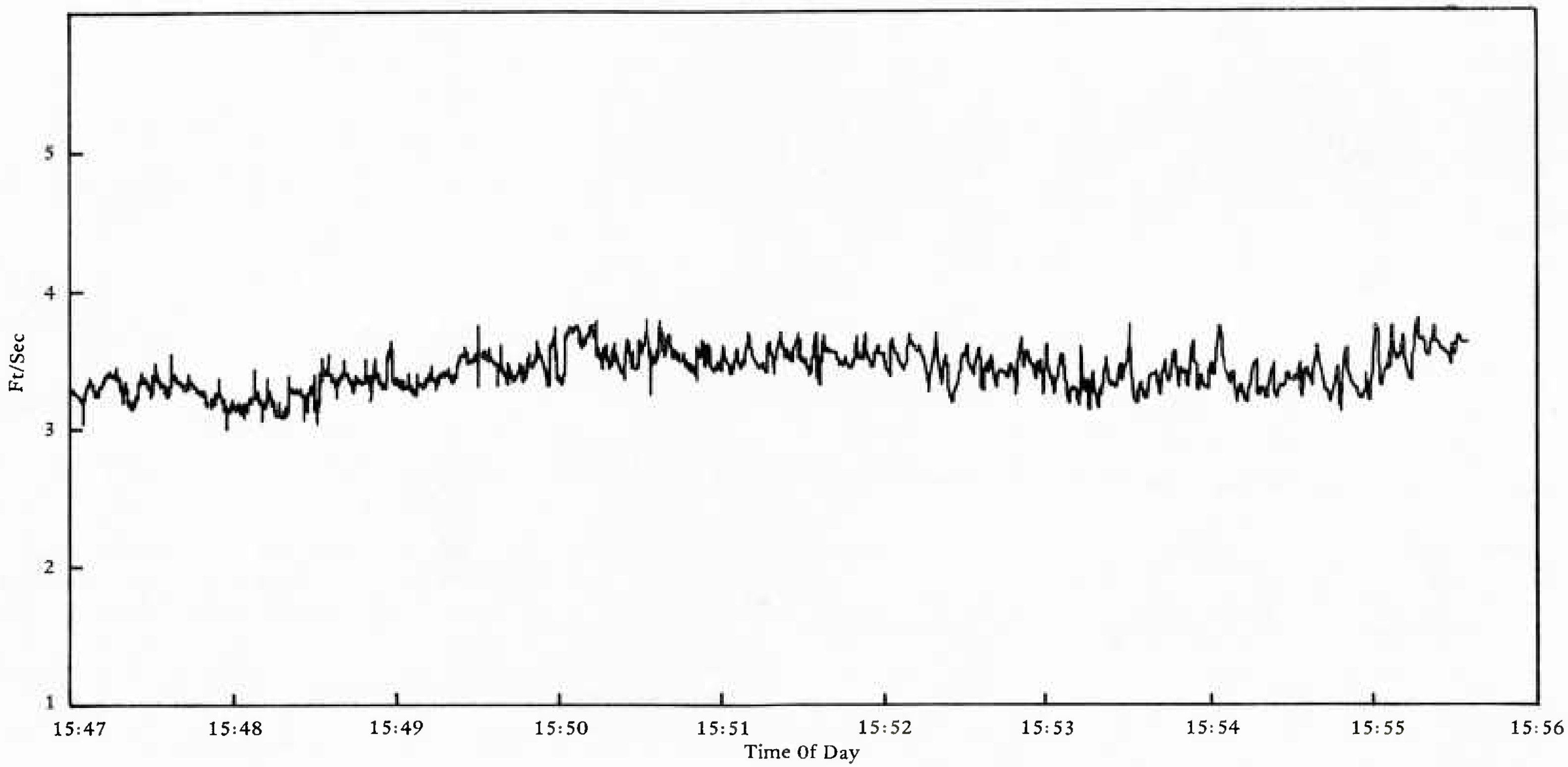


Figure B-1. Representative instantaneous currents.

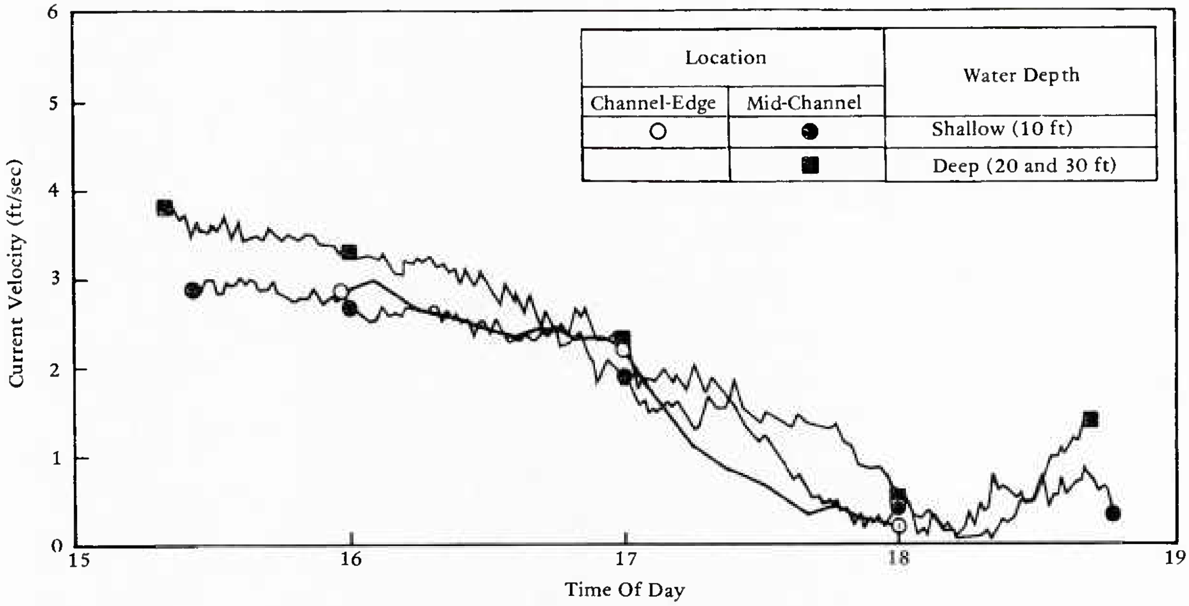
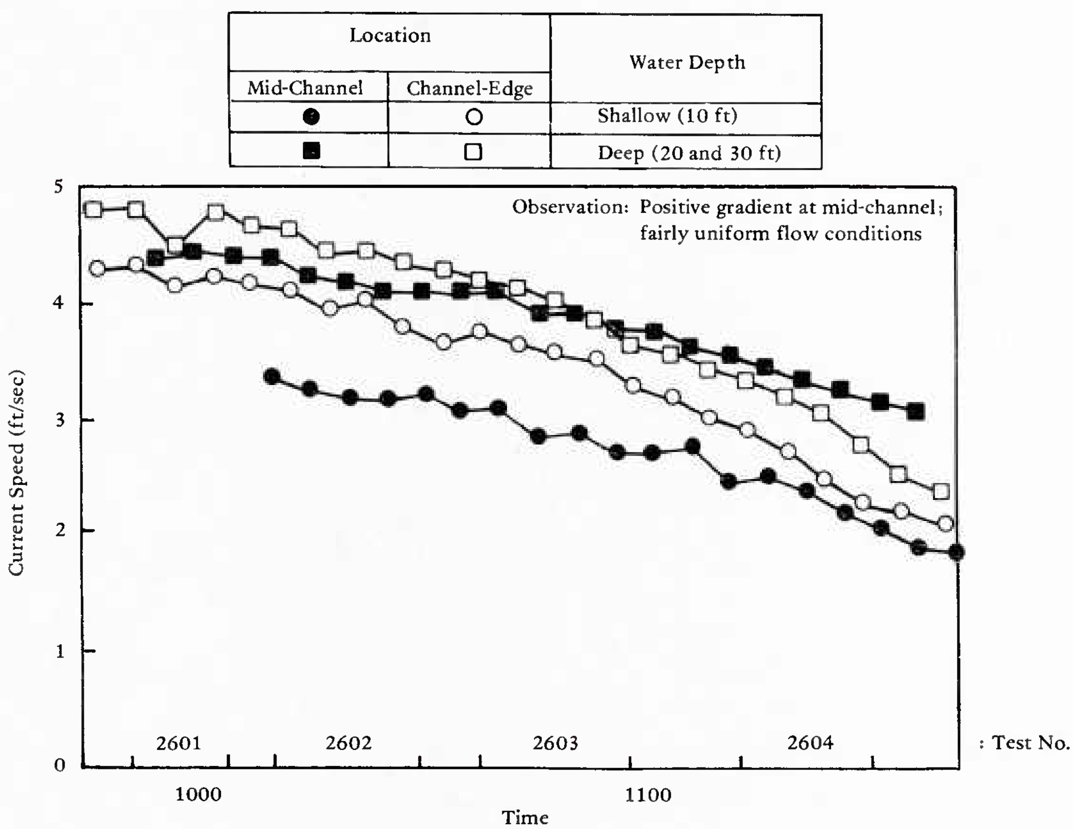
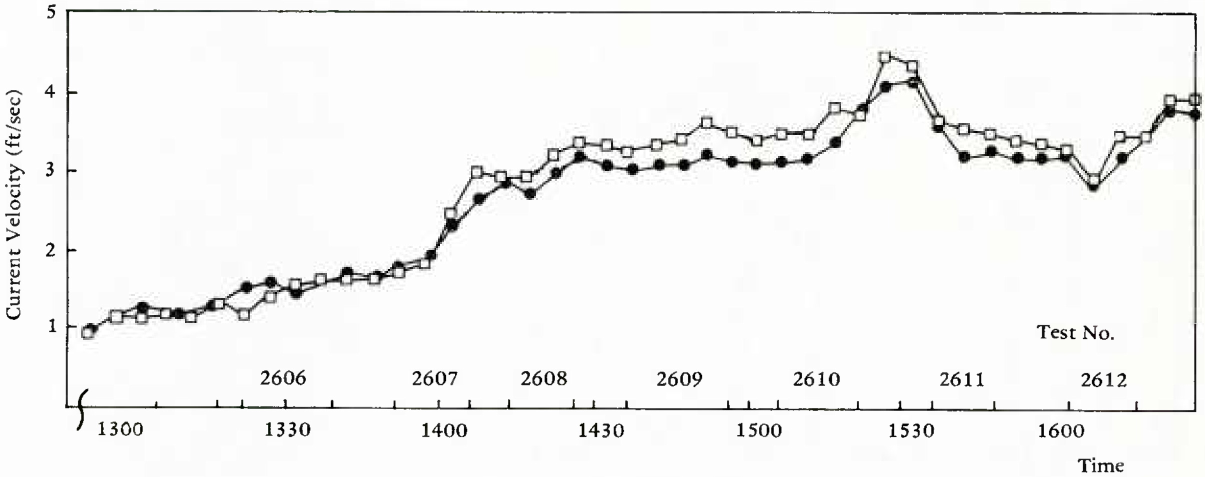


Figure B-2. Current measurements from the T-2 tests.



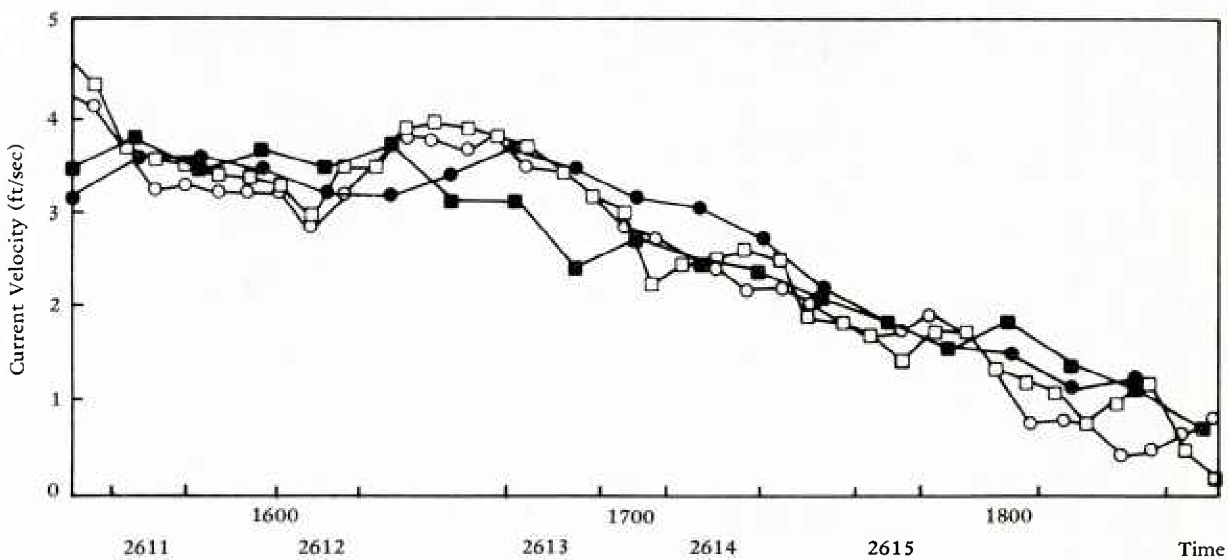
B-2. Continued

Location	Water Depth
Channel-Edge	
●	Shallow (10 ft)
□	Deep (20 and 30 ft)



B-2. Continued

Location		Water Depth
Mid-Channel	Channel-edge	
●	○	Shallow (10 ft)
■	□	Deep (20 and 30 ft)



B-2. Continued

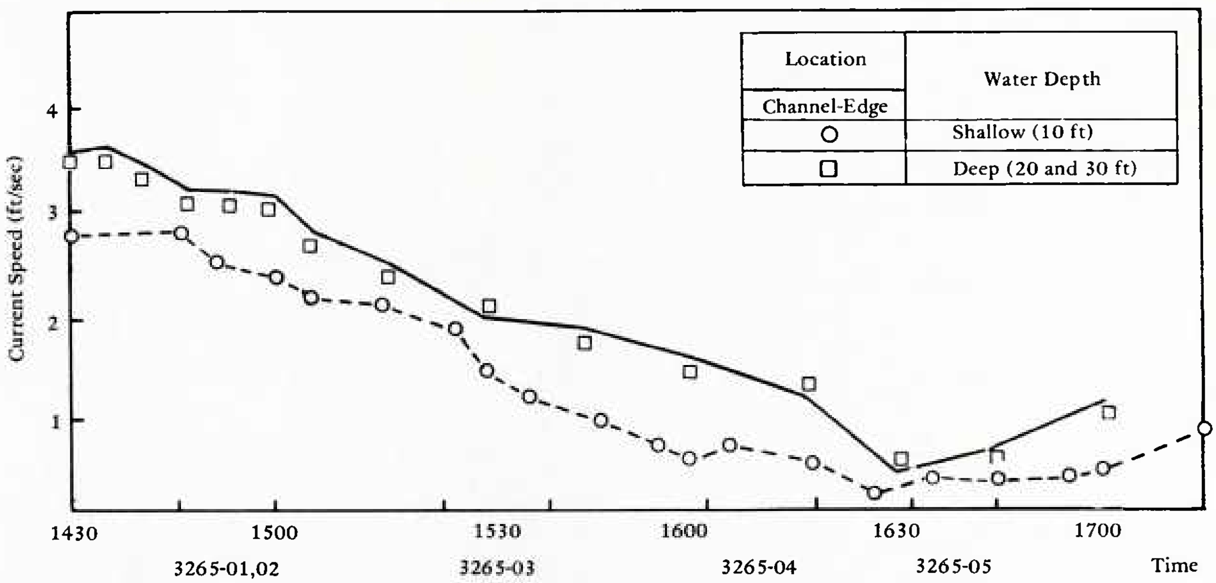


Figure B-3. Current measurements from the DD-964 tests.

Appendix C

IDENTIFICATION OF FLOW PHENOMENA

The primary objective of these tests was to collect reliable data for validating current loads methodologies. This information is presented in the main text as design coefficients. For many of the tests, the behavior of these coefficients corroborates that the basic flow phenomena are well understood; the Reynolds Number dependence of the deep water lateral force coefficient is a good example.

However, some of the coefficients exhibited behavior that is contrary to expectations. In these cases the flow phenomena and associated force behavior are not as well understood. For example, the sign reversal of the shallow water yaw moment coefficient at a constant current angle is fundamentally different compared to the expected constant coefficient. A better understanding of the flow phenomena is required in these latter cases before design coefficients can be confidently established.

Information on the basic flow phenomena is available from two sources from these tests. First, direct measurements were taken of the three-dimensional velocities in the wake of the T-2 tanker.* Velocity profiles were taken at 5-foot depth increments at 10-, 20- and 30-foot distances downstream from the hull. The incident current was essentially beam-on. Mean and dynamic velocity components are presented.

Second, some qualitative information is indirectly available from the hawser force measurements. If the hull was inducing vortices off the bow and stern in the horizontal plane, the oscillating wakes would produce out-of-phase dynamics in the bow and stern hawser forces. Figure C-1 shows hawser forces from test 2501. There is a regular pattern of oscillations with a 65-second period in both records. However, the forces are in-phase, which is contrary to the expected behavior. Figure C-2 shows the same forces for test 2502. Dynamics are still present, still in-phase, but with a 94-second period. Also, observe that the stern force dynamics are larger than the bow force dynamics for both tests. These oscillations do not appear to be related to any natural frequency of the mooring system because the frequencies are too low, no major vessel displacements were detected, and the amplitudes do not damp out.

These observations show that the flow phenomena are probably the same in both tests. Further analyses of these and other test data may lead to an improved understanding of the flow, with a corresponding improvement in the resolution of design coefficients.

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*Naval Civil Engineering Laboratory. Technical Memorandum M-44-84-06: Three dimensional flow-measurements behind a tanker in a beam current, by P. Palo, N. Gwinn, and A. Smith. Port Hueneme, Calif., Sep 1984.

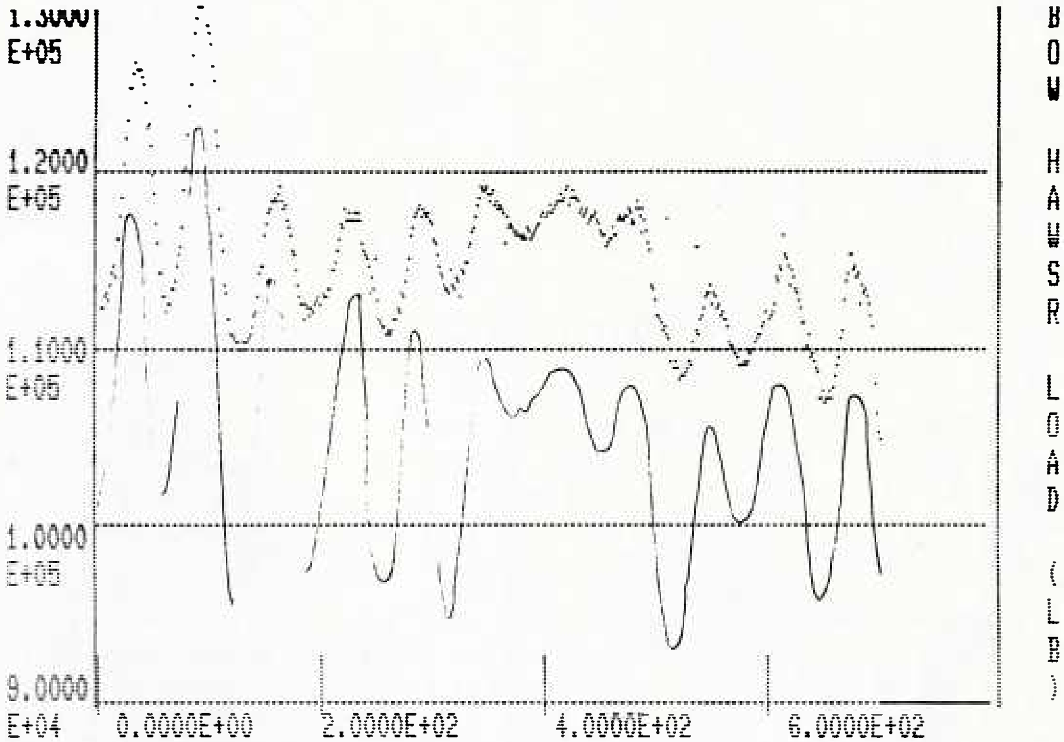

Figure C-1. Hawser load versus time, test 2501.

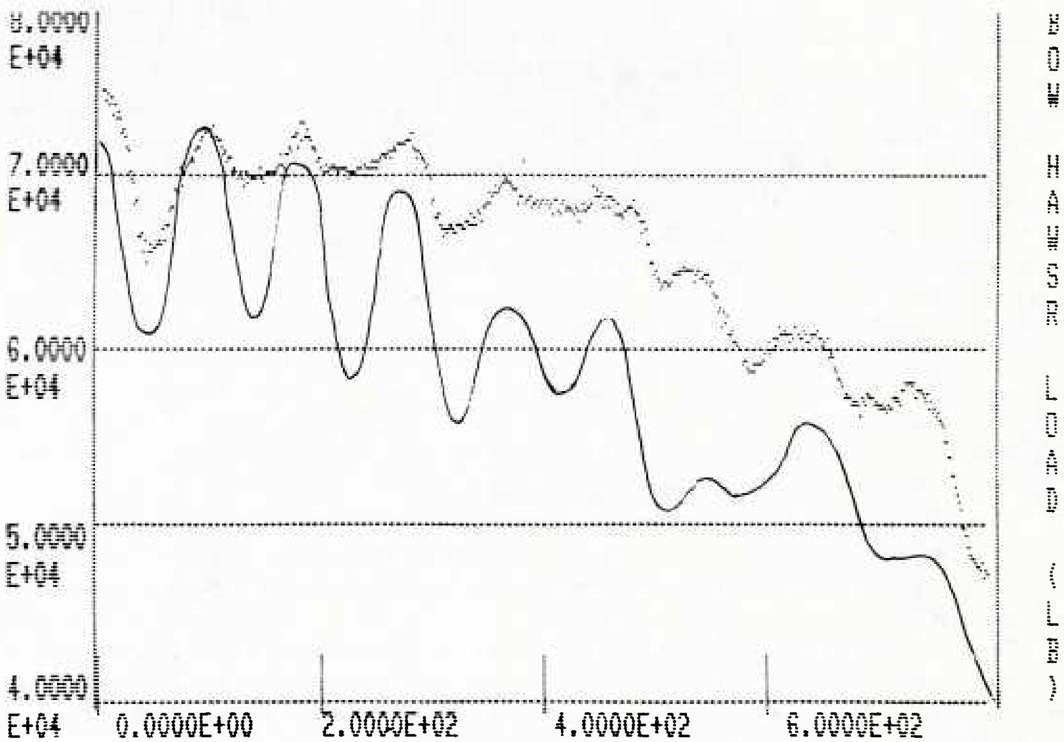

Figure C-2. Hawser load versus time, test 2502.

Appendix D

THEORETICAL ANALYSIS OF THE MEASUREMENTS

The deep water yaw moment coefficients shown in Figure 18 are functions of too many parameters to allow for meaningful interpretations. An effort was made to theoretically account for these parameters and allow for extrapolation to level hull-uniform flow conditions for all the tests. This analysis was unsuccessful, but a brief description of the technique may prove valuable in guiding future attempts.

GENERAL APPROACH

The model was based on the assumption that each section of the hull had a unique, two-dimensional, lateral force coefficient due to its local beam-to-draft ratio, its bilge keel (rounding) radius, and any applicable end effect that allowed the flow to become three-dimensional. These local coefficients were calculated using general drag information* and normalized by the mid-ships coefficient.

The result was a series of "known" relative factors for each section times an unknown coefficient magnitude (representing mid-ships). This unknown coefficient was calculated using these sectional factors, along with sectional areas and velocities, and the measured lateral force.

A similar procedure was also used based on the same factors, areas and velocities, but moment arms to each section were added, and the same unknown mid-ships coefficient was solved using the measured yaw moment.

Since the lateral drag and yaw moment are physically related, these two calculated coefficients should match for each test.

RESULTS

The agreement between the coefficients was not found to be consistent enough to demonstrate that the calculated coefficients were correct. This is not surprising, since the variations evident in the T-2 shallow water yaw moment coefficients imply that it is incorrect to assume that the flow at each section behaves independently of the neighboring sections. Therefore, a simple strip theory with independent superposition forces will not accurately model this phenomenon.

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*S. Hoerner. Fluid-dynamic drag. New Jersey, 1965.

Appendix E

LONGITUDINAL FORCE CALCULATIONS

LONGITUDINAL CURRENT FORCE COMPONENTS

There are several terms required to calculate the total longitudinal force on a ship (see LIST OF SYMBOLS for definitions). These terms are usually represented as follows:

$$X_T = X_f + X_r \tag{E-1}$$

where the X_r term is made up of the following components:

$$X_r = X_F + X_p + X_a + X_b \tag{E-2}$$

All of the above terms are estimated using the same generic equation:

$$X = \frac{1}{2} \rho V^2 A C_D \tag{E-3}$$

The form drag coefficients are considered constant. The friction drag coefficient, however, is a function of Reynolds Number. For these tests the Reynolds Number range was small, and this coefficient can also be assumed to be constant. This equation can, therefore, be further simplified into the following form:

$$X = k V^2 \tag{E-4}$$

where $k = 0.5 \rho A C_D$.

This simplification implies that the total drag force (X_T) for a specific ship can be quickly calculated for any current velocity once the constant k terms have been precalculated and summed. Using the same nomenclature as above, X_T can be estimated using a total coefficient (K):

$$X_T = K V^2 \tag{E-5}$$

where

$$K = k_f + k_F + k_p + k_a + k_b \tag{E-6}$$

DD-964 FORCE

Table E-1 lists the parameters used to calculate K for the DD-964 using Equation E-6.

The approximate expression for the total longitudinal force on vessels in the DD-964 is found by summing the k values in Table E-1:

$$K = (91 + 30 + 384 + 110 + 19) = 630$$

Therefore,

$$X_T = 630\ V^2 \quad (X_T \text{ in lb if V is in ft/sec}) \tag{E-7}$$

The relative contributions from the various terms can be found using the values in Table E-2 (e.g., propeller drag is (384/630) or 61% of the total force).

T-2 FORCE

Table E-2 lists the component k values used to calculate the T-2 longitudinal force. The total K value is then 530.

COMPARISON OF EXPERIMENTAL AND CALCULATED FORCES

The easiest comparison between the calculated and experimental forces is to convert the experimental data points into the equivalent k value summed above in Equation E-7. These k values are shown in Tables 10 and 11 and Figure 21.

The calculated K value for the DD-964 is correct over the higher range of current speeds. The calculated K for the T-2 corresponds to an average of the experimental k's.

If the T-2 hull drag term is neglected, the K value drops to 435. This is clearly too low. The smaller hull form drag coefficient used for the DD-964 is a compromise between the need to use a hull form drag for the T-2 and the fact that the DD-964 drag force can be calculated quite accurately without including that term.

Existing methodologies for calculating longitudinal drag do not include a term for hull form drag. This seems to be a consequence of extrapolating resistance relationships for high speed longitudinal drag (where hull form drag is negligible) rather than an evaluation of the low speed problem. Reference E-2 presents results from Reference E-3, which shows that form drag is a function of the length to diameter (L/D) ratio for bodies of revolution. The percent of form drag to total drag was found to be 5, 17, and 30 as the L/D ratio decreased from 10 to 5 to 3.33, respectively. For the test vessels considered here, L/D is either (length/beam) or [length/(two times draft)]; either relationship shows a L/D ratio of 8 to 10. Using this guidance and the DD-964 asymptotic experimental K value of 500, then the k_F should be about 30. The corresponding drag coefficients (from Tables E-1 and E-2) would be 0.03 and 0.02 for the DD-964 and T-2, respectively. The larger value of 0.06 was selected for the T-2 to reflect the less streamlined hull shape compared to the DD-964.

REFERENCES

E-1. David Taylor Naval Ship Research and Development Center. Report 1625: Windmilling and locked shaft performance of supercavitating propellers, by R. Hecker. Bethesda, Md., Jul 1962.

E-2. J.P. Comstock, editor. Principles of naval architecture, revised edition. New York, N.Y., Society of Naval Architects and Marine Engineers, 1967.

E-3. Aero Research Committee. R&M 1874: The calculation of the total and skin friction drag of bodies of revolution at zero incidence, by A.D. Young. London, England, 1939.

Table E-1. DD-964 Longitudinal Force Components

Variable	Area (ft^2)	Drag Coefficient	k	Comments
k_f	36,340	0.0025	91	ITTC coefficient + 0.005
k_F	1,000	0.03	30	Estimate[a]
k_p	320	1.2	384	C_D from Reference E-1; 17-ft diameter used
k_a	110	1.0	110	Very approximate C_D
k_b	95	0.2	19	C_D for turbulent flow on sphere

[a]See discussion in COMPARISON OF EXPERIMENTAL AND CALCULATED FORCES section.

Table E-2. T-2 Longitudinal Force Components

Variable	Area (ft^2)	Drag Coefficient	k	Comments
k_f	43,200	0.002 + 0.001	162	ITTC coefficient, with 50% added for fouling
k_F	1,564	0.06	95	Estimate only[a]
k_p	209	1.2	251	C_D from Reference E-1
k_a	15	1.2	20	Rudder only

[a]See discussion in COMPARISON OF EXPERIMENTAL AND CALCULATED FORCES section.

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